Radio and Electronic Components: Volume Three

FIXED CAPACITORS

BY

G. W. A. DUMMER

M.B.E., M.I.E.E., Sen. Mem. I.E.E.E., M.Brit. I.R.E.

Royal Radar Establishment, Ministry of Aviation

SECOND EDITION

LONDON

SIR ISAAC PITMAN & SONS LTD.

First published 1956
Second edition 1964

SIR ISAAC PITMAN & SONS LTD.
PITMAN HOUSE, PARKER STREET, KINGSWAY, LONDON, W.C.2
THE PITMAN PRESS, BATH
PITMAN HOUSE, BOUVERIE STREET, CARLTON, MELBOURNE
22–25 BECKETT'S BUILDINGS, PRESIDENT STREET, JOHANNESBURG

ASSOCIATED COMPANIES
PITMAN MEDICAL PUBLISHING COMPANY LTD.
46 CHARLOTTE STREET, LONDON, W.1
PITMAN PUBLISHING CORPORATION
20 EAST 46TH STREET, NEW YORK 17, NEW YORK
SIR ISAAC PITMAN & SONS (CANADA) LTD.
(INCORPORATING THE COMMERCIAL TEXT BOOK COMPANY)
PITMAN HOUSE, 381–383 CHURCH STREET, TORONTO

©
G. W. A. Dummer
1964

MADE IN GREAT BRITAIN AT THE PITMAN PRESS, BATH
F4—(T.814)

FOREWORD

(Contributed to Volume I, 1956)

BY

SIR ROBERT RENWICK, BT., K.B.E.

(*President of the Radio and Electronic Components Manufacturers' Federation*)

FEW people outside the electronics industry appreciate the vastness of the field in which radio components are now being used. Domestic radio and television sets absorb well over a million components a day, yet this figure is several times surpassed by the number of components made for telecommunications equipment, navigational aids, radar installations, industrial electronics, etc. This field is being steadily widened as the scope of electronics expands in nuclear electronics, computors for business machines, medical electronics, guided weapons control systems, etc. Some 40,000 people in over 150 factories are now being employed in the radio and electronic components industry alone and component parts are being made at the rate of four million pieces a day, while exports of components have reached the figure of some £1 million per month. The importance of this effort to the nation cannot be over-emphasized and the component industry is rightly proud of its fine achievements.

In spite of the size and importance of this industry there have not been any books on components such as resistors and capacitors until the author introduced this series. I am sure the value of these books will become immediately apparent and will increase as the electronics industry grows and expands its spheres of activity. This first book on "Fixed Resistors" is an authoritative volume, rightly written from the point of view of the user. It sets out to help him in choosing the right resistors for his purpose, and the comparison charts of the characteristics of many different types of resistor are most valuable in helping this choice. It covers every aspect of fixed resistor design and usage, and if the remaining volumes are as comprehensive in their coverage of the field, they should certainly fill a wide gap in the present technical literature.

I can imagine few people more qualified to write these books than the author. He had a long background of experience in the radio industry before he joined the Telecommunications Research Establishment in 1939, where he created a group working on radar synthetic

trainers during the early part of the War. The ingenuity and complexity of some of the circuits used must have given him valuable experience in the practical use of components. He was awarded the M.B.E. for his work on radar trainers during the War and was also awarded the American Medal of Freedom (with Bronze Palm) by the United States of America for his contribution to this field.

In 1944 he began research and development of components for radar equipments and is now head of a team of specialists working on components and techniques at the Radar Research Establishment. He is an I.E.E. Premium Award winner, has written many authoritative articles on components and techniques affecting components, and has travelled and lectured extensively. He is a member of the Joint Services Radio Components Research and Development Technical Committee and the Radio Components Standardization Committee. He is also chairman of the R.C.R.D. sub-committee on Fixed and Variable Resistors, and chairman of the R.C.R.D. Panel on Transistor Components. He is chairman of the N.A.T.O. sub-committee on the standardization of Resistors, and represents the United Kingdom on the N.A.T.O. sub-committee for the standardization of Capacitors.

I think the introduction of this series of books is timely and I am certain that they will make a valuable contribution to the designer's knowledge of radio and electronic components. I hope they will aid British Industry in the production of electronic equipments.

PREFACE

It has been said that components are the bricks with which all electronic equipments are built and that the reliability of a modern complex electronic equipment is determined by the reliability of the weakest component. A wider knowledge of the characteristics of components should, therefore, help designers and users of all types of equipments. This book has been written from the viewpoint of the user, to enable him to choose the best component for his particular requirement and to understand its fundamental characteristics. Component development takes place comparatively slowly and often several years elapse between the original research work and full production of a component. Minor modifications and changes may occur, and component manufacturers are usually pleased to provide any such information on their products.

As the range of components is so wide they are covered in several volumes, of which this is the third. The first and second volumes deal with Fixed and Variable Resistors and the fourth and fifth volumes with Variable Capacitors, and Wires and R.F. Cables, in a similar manner. These volumes cover the most common types of component; others may follow on plugs and sockets, switches, etc.

No bibliography appears to exist that deals specifically with radio and electronic components. The author has, therefore, collected some 880 references to fixed capacitors to form a reasonably extensive bibliography on the subject. Similar biographies are included in the volumes dealing with other types of components.

In this second edition the comparison charts of characteristics have been omitted and the data incorporated in the appropriate chapter. In addition, the *British Miniature Components Data Annual** is now available which gives full details of all miniature components. A new chapter has been added in this edition, on "Dielectric film evaporation and deposition techniques," in view of the rapid advance of microminiaturization. I hope that these books will fill a gap in the technical literature and will aid British industry in the development and production of electronic equipments.

G. W. A. D.

* Pergamon Press.

ACKNOWLEDGMENTS

IT is obvious that this book could not have been written without the generous assistance of a large number of people and the author takes pleasure in acknowledging the help received from the following: J. R. Balmer, R. M. Barnard, J. H. Bruce, S. J. Borgars, G. P. Britton, P. R. Coursey, R. J. Cook, A. A. Dyson, G. C. Gaut, P. Lloyd, H. G. Manfield, C. H. Miller, F. C. Robinson, L. W. D. Sharp, P. A. Sporing, C. Shaw, C. H. Taylor, E. H. Toder, W. Wilson and D. F. Urquhart. The author's thanks are due to C. G. Garton for reading proofs and making valuable comments and suggestions. Other acknowledgments are made in the text. In addition, much help has been received from many component manufacturers who have provided information about their products.

The views expressed herein do not necessarily represent the views of the Ministry of Aviation, and the author has endeavoured to be impartial in assessing the characteristics of the components described.

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CHAPTER 1

GENERAL INFORMATION ON COMPONENTS

A BRIEF HISTORY OF COMPONENT DEVELOPMENT IN GREAT BRITAIN

THE first radio components incorporating resistance, inductance and capacitance might be considered to be the constituent parts of the Hertz loop, although the Leyden jar had been used as a capacitor for many years, and resistors had previously been used in the field of electrical power.

Faraday, in the 1850's, discovered that silver sulphide possessed a high negative temperature coefficient of resistance, anticipating the modern thermistor, and in the late 1880's the first aluminium electrolytic capacitor was made in Germany.

The first carbon-composition resistor was made as far back as 1885, and the first inductor for radio purposes might well be considered the Hertz loop itself in 1887. The two-electrode valve was introduced in 1904 and the three-electrode valve in 1907, and with the growth of radio telegraphy using these valves, transmitters and receivers were designed and built, with the designer of the equipment constructing all the necessary components.

The 1914–18 War gave a marked impetus to the development of radio communications, and with the advent of the three-electrode valve in quantity, components began to assume the form roughly as we know them now. After the First World War the component industry itself began to develop. The British Broadcasting Company started programme broadcasting on 14 November, 1922, and from about that time up to about 1930 many component manufacturers began to specialize in individual components, from which the home constructor used to make radio receivers. Resistors were used in large quantities as grid leaks, anode loads, etc., and consisted of carbon compositions of many kinds compressed into tubular containers and fitted with end caps. Paper-dielectric capacitors were mainly tubular types enclosed in plain bakelized cardboard tubes, with bitumen or similar material sealing the ends. The terminations were frequently brought out radially and not axially. Bakelite-enclosed stacked-mica capacitors, fitted with screw terminals and with the bottom of the case sealed with bitumen, were also in common use. Rectangular metal-cased and plastic-cased types were also used. Electrolytic capacitors were mainly wet types in tubular metal cases. Cracked-carbon film-type resistors were introduced from

Germany in about 1928 and by 1934 were being manufactured in quantity in this country.

From 1930 onwards the home construction of sets diminished and many component manufacturers and radio set makers worked together. Techniques for component manufacture in quantities improved, and some ten million radio sets were in use in the United Kingdom in 1939. The standards to which components were made were those of domestic radio. Pan-climatic protection was unnecessary and the self-compensating action of the radio valve made wide tolerances and poor stability generally acceptable. Apart from certain electrical engineering applications, telephone companies, a few sections of the instrument industry and the Services, no very high standard was required of the component manufacturer. The first step towards improved components was taken in 1938, when the Royal Aircraft Establishment began type-approval tests to Wireless Telegraphy (W.T.) Board Specification K 110, on a wide range of components for Air Force use. Directorate of Communications Development (D.C.D.) specifications were drawn up and standard lists of components prepared.

The 1939–45 War made it essential to produce large quantities of components quickly. The introduction of radar into the Services meant that still more components, including many new types, were required. The need for increased production, which amounted to approximately three times the normal peace-time output, and the shortage of materials led to Inter-Services rationalization of components, commencing in 1941 with the formation of the Inter-Services Communications Components Committee (I.S.C.C.) and followed by the formation of the Inter-Services Components Technical Committee (I.S.C. Tech.C.) in 1942—now the Radio Components Standardization Committee (R.C.S.C.). An example of the success of this rationalization is that in 1942 there were 1,500 different plugs and sockets in use in the Ministry of Aircraft Production alone, and after rationalization only 200 were retained by the *three* Services. Other examples are—some 10,000 different resistor types were reduced to 1,300 preferred items; 8,000 fixed-capacitor types were reduced to 750 preferred items; and 700 types of transformer laminations were reduced to 32 preferred items. Similar reductions were made in other components. Inter-Services technical specifications for components were also drawn up by the I.S.C.Tech.C. and these are constantly being revised by the R.C.S.C. These specifications were, and still are, purchasing documents, and they also contain the inspecting procedure for accepting components and for type approval.

It was becoming apparent by 1942 that major improvements in component design were necessary, and in 1943 the Joint Services Radio Components Research and Development Committee (R.C./R.D.C.) was

formed to stimulate and co-ordinate research and development on new components and materials. Experience in the Pacific war emphasized the defects in component design under conditions of prolonged humidity and led to the necessity for improved sealing. Pressurized and sealed equipments required components which would operate at high temperatures. Pack sets and miniature equipments led to effort being devoted to reducing the size of components and many miniature types were introduced. High precision was also required in components for radar systems and for multi-channel communication receivers, etc. All this led to establishments and industry, often sponsored by the R.C./R.D.C., developing new materials and components intended to satisfy the many conflicting requirements.

Waxed tubular paper-dielectric capacitors and some metal-cased types were replaced by metal-cased tubular types with Neoprene end seals. Metallized paper-dielectric capacitors were developed. Improved control of the temperature coefficient of ceramic-dielectric capacitors was introduced by manufacturers and new high-permittivity ceramic mixes developed. Glass-enclosed and sealed Grade 1 fixed resistors were developed but did not go into production. Many manufacturing improvements were introduced into Grade 2 resistor production and testing. Work on sealed variable resistors was sponsored by the R.C./R.D.C., and many types are now available. Transformers operating at higher temperatures, oil-filled and sealed in metal cans, were developed and, more recently, resin "potted" transformers have been introduced. Sealed relays and indicating meters were also designed and produced.

All these developments resulted in improved components for use by the Services, and the component of today bears little resemblance to its earlier counterpart, being smaller and lighter, and operating over a wider temperature range under adverse climatic conditions. Even so, modern requirements ask for still higher standards, particularly in reliability, and, with the advent of the transistor, still more miniaturization. There is little doubt, therefore, that research and development work will continue in order to improve the performance of components even as we know them today.

Microminiaturization techniques have led to the development of thin-film components and have made a major change in the shapes of components for the first time in many years. Recent developments in semiconductor components, where they are fabricated directly with no interconnections, again are making a major change in shape.

TEMPERATURE AND HUMIDITY CATEGORIES OF COMPONENTS

In 1939, temperature and humidity tests for Service components were to the W.T. Board Specification K 110. This consisted of a dry heat

test (6 hr at 70°C) followed by two humidity cycles (6 hr at 60°C and 95 per cent relative humidity). Early in the war, a cold cycle was introduced (at −30°C) between the two humidity cycles. The spread of the war into different climates, and the arduous operational conditions, led to a new specification, RCS 11, which superseded K 110

TABLE 1.1. TEMPERATURE AND HUMIDITY CATEGORIES OF COMPONENTS
Service Categories—Specification DEF 5011

1. *Temperature Categories*

Category	Temperature Range (°C)
T.1	−25 to +70
T.2	−55 to +70
T.3	−55 to +85
T.4	−55 to +100
T.5	−55 to +125
T.6	−55 to +150
T.7	−55 to +200
T.8	−65 to +100

2. *Humidity Classifications*

Class	Conditions	
	1st Group	2nd Group
H.7	6 accelerated damp heat cycles (16 hours at +53 to 57°C, 95% R.H.)*	56 days damp heat (continuous at 38 to 42°C, 90 to 95% R.H.)
H.6	As above	As above
H.5	2 accelerated damp heat cycles	21 days damp heat
H.3	1 accelerated damp heat cycle with assisted recovery	4 days damp heat with assisted recovery

* *N.B.* H.7 has four extra cold cycles alternating with the last four humidity cycles—the sequence ending with a humidity cycle.

and was, in turn, superseded by Defence Specification DEF 5011. The temperature and humidity categories for this specification are given in Table 1.1.

For commercial components the Radio Industry Council introduced Specification RIC 11. This specification is now similar to B.S. 2011,

which was introduced in 1954. The tests for components in these categories are summarized in Table 1.2.

An International Electrotechnical Commission (I.E.C.) Specification No. 68—"Basic climatic and mechanical robustness testing procedure

TABLE 1.2. TEMPERATURE AND HUMIDITY CATEGORIES OF COMPONENTS
B.S.I. Categories—Specification B.S. 2011 : 1954

1. *Temperature*

Temperature Range	Category Numbers
−40°C to +100°C	40/100
−40°C to +85°C	40/85
−40°C to +70°C	40/70
−25°C to +70°C	25/70
−10°C to +55°C	10/55
−10°C to +40°C	10/40

2. *Humidity Classification*

Class	Conditions	
	1st Group	2nd Group
H.3	1 accelerated damp heat (16 hours at 55°C, 95% R.H.) plus assisted drying	7 cycles tropical exposure 35°C ± 2°C and 20°C ± 5°C. Upper temp. ⩽12 hr; lower temp. ⩽5 hr. Plus assisted drying
H.3A	None	As above but no assisted drying
H.2	2 accelerated damp heat cycles (as above)	28 cycles (as above)
H.1	6 accelerated damp heat cycles (as above)	84 cycles (as above)

for components for radiocommunication"—is now available and is summarized in Table 1.3.

Whilst the salient points in these three specifications have been summarized briefly, it should be remembered that these categories are subject to amendment by the authorities concerned.

VIBRATION AND SHOCK CATEGORIES

In Specification RCS 11, a vibration resonance search (10 to 150 c/s) test was incorporated mainly to cover transport vibration frequencies.

TABLE 1.3. TEMPERATURE AND HUMIDITY CATEGORIES OF COMPONENTS
I.E.C. Categories—Specification IEC 68

Severity	Temperature (°C)		Humidity
	Dry Heat	Cold	
2	155	—	—
3	125	−65	—
4	100	−55	6 accelerated humidity cycles (16 hours at 55°C, 95% R.H.) 56 days long-term damp (continuously at 40°C, 95% R.H.)
5	85	−40	2 accelerated humidity cycles (as above) 21 days long-term damp (as above)
6	70	−25	4 days long-term damp (as above)
7	55	−10	1 accelerated humidity cycle (as above) plus 6 hours assisted drying 4 days long-term damp (as above) plus 6 hours assisted drying
8	40	—	2 accelerated humidity cycles (as above) 10 days long-term damp (as above)

N.B. Components can be classified in groups of any combination of the above categories. Three figures are quoted—

1st . . low temperature
2nd . . high temperature
3rd . . humidity severity

e.g. Group 454 = −55°C, +85°C and humidity severity 4.
Group 666 = −25°C, +70°C and humidity severity 6.

Early in 1961, Specification DEF 5011 introduced additional endurance vibration testing in addition to wider vibration frequencies (5 to 5,000 c/s). Acceleration tests at 13*g*, 50*g* and 100*g* applied for five minutes, together with shock tests of 4,000 bumps at 1 inch amplitude, were also introduced in this specification. B.S. 2011 also introduced vibration and shock testing, and the tests in both specifications are summarized in Table 1.4.

MISCELLANEOUS CATEGORIES

Other tests, such as mould growth, salt spray, soldering, low air density, etc., are also required and Table 1.5 summarizes these test specified in Specification DEF 5011.

GENERAL COMPONENT SPECIFICATIONS AND PUBLICATIONS

There are a number of general component specifications which are of value to users—mainly those issued by the Radio Industry Council and British Standards Institution on behalf of the radio industry and those issued by the Radio Components Standardization Committee or H.M.S.O. as Defence (DEF) Specifications on behalf of the Services.

TABLE 1.4. COMPONENT ENVIRONMENT TEST SPECIFICATION

Shock and Vibration Requirements

	DEF 5011			British Standard B.S. 2011	
Vibration	*Severity Class* 1 Frequency Range 5–500 c/s, $3{\cdot}5\pi$ in. per sec, 5 to 60 c/s then $10g$ up to 500 c/s		Endurance 10 hr total, shared equally between resonances having $Q \geqslant 3$, or 10 hr constantly sweeping if no resonances	Frequency Range 10–150 c/s up to $10g$	If resonance observed, 10 hr at each resonance
	Severity Class 2 Frequency and Amplitude as Class 1		Endurance 144 hr at each resonance having $Q \geqslant 3$. If resonant-free, 96 hr at three selected frequencies		
	Severity Class 3 Frequency 5 to 5,000 c/s Amplitude Resonance search up to $2g$, 5–5,000 c/s Endurance—100 hr sweeping at $10g$, 30–2,000 c/s Functional, if required by component specification $30g$, 30–5,000 c/s				
Acceleration (sustained)	Severity A1 Severity A2 Severity A3	$13g$ $50g$ $100g$	Applied for 5 min in each plane and sense	None	
Shock Bump	4,000 bumps. 1 inch free drop peak deceleration $40g$			4,000 bumps, 1 inch free drop into rubber, peak acceleration $40g$	
Shock Pulse	*Severity*	*Square Pulse*	*Rise Time*	*Duration*	
	1	$50g$	0·25 to 0·5 msec	12 msec	None
	2	$75g$	0·5 to 1 msec	6 msec	
	3	$100g$	0·5 to 1 msec	6 msec	

TABLE 1.5. TESTS IN SPECIFICATION DEF 5011 SUMMARIZED IN ALPHABETICAL ORDER

Acceleration	A1 13*g*, A2 50*g*, A3 100*g*; 5 min in each plane and sense (total 30 min)
Air Density	D1 = 0·370 (30,000 ft) D2 = 0·014 (100,000 ft) D3 = 0·003 (130,000 ft)
Bumping	4,000 bumps at 40*g*, at high and/or low temperature
Damp Heat Accelerated	55°C ± 2°C 95 to 100 per cent R.H. (cyclic variation 2 to 3°C). Duration 16 hr plus 5 hr cooling
Damp Heat Long-term	40°C ± 2°C R.H. 90 to 95 per cent H3 4 days, H5 21 days H6 and H7 56 days
Endurance	2,000 hr at upper category temperature with electrical load applied
Fire Risk	In flame 60 sec max. Extinguish in 15 sec
Humidity Classes	H6 6 damp heat (accelerated) 56 days H5 2 damp heat (accelerated) 21 days Plus further 14 days for information H3 1 damp heat (accelerated) plus 4 days new long-term damp heat H7 New class—similar to H6 but includes 4 cold cycles (*Note:* H4 Commercial class —omitted)
Mould Growth	26–30°C, 95–100%, R.H. for 28 days
Robustness of Terminations	Tensile Bending Torque Torsion
Salt Mist	Spray 2 hr 15°C to 35°C. Store 7 days at 33–37°C, 90–95 per cent R.H. Repeat for total of 28 days
Sealing	Differential pressures—2, 14 and 45 lb/in.^{2}
Shock	3 severities— S1 50*g* duration 12 msec S2 75*g* duration 10 msec S3 100*g* duration 6 msec
Shelf Life	3 years under natural conditions of temperature, humidity and air pressure

TABLE 1.5—*contd.*

Soldering	*Iron:* Temp. 300°C to 350°C Medium and small bit sizes Tinning within 2 sec Heat resistance further 8 sec *Bath:* Temp. 245–255°C Tinning 2 sec $\pm \frac{1}{2}$ sec Heat resistance. 350°C $\pm$ 10°C Further 3 to 4 sec
Standard Atmospheric Conditions *Reference*	(i) Temp. 20°C, 1,000 mb (ii) Temp. 19–21°C R.H. 63–67 per cent Pressure 860 -1,060 mb
Measurements	Temp. 15–35°C, R.H. 45–75 per cent Pressure 860–1,060 mb, recovery within $\pm$1°C of lab. temp. R.H. 73–77 per cent
Assisted recovery	Pressure 860 to 1,060 mm Hg R.H. 20 per cent 6 hr 53–57°C
Sequence of Test Conditions	(i) Mechanical followed by rapid change of temp.; Dry heat; Dry cold; Low air-density; Accelerated damp heat; Soldering and fire risk (ii) Long-term damp heat (iii) Endurance (iv) Shelf life (v) Biological (vi) Corrosion
Temperature Categories	T1 25/70 T2 55/70 T3 55/85 T4 55/100 T5 55/125 T6 55/150 T7 55/200 T8 65/100
Temperature Dry Cold	3 Severities—25°C —55°C —65°C Period: 2 hr (or as specified)
Temperature Dry Heat	6 Severities + 70°C + 85°C +100°C +125°C +150°C +200°C
Temperature Rapid Change	One hour at each upper and lower temperature limit of severity, with 3-min change-over period. Total of 10 cycles

TABLE 1.5—*contd.*

Vibration	3 Severities: V1 *5 c/s* to *500 c/s* Constant velocity $3{\cdot}5\pi$ in./sec from 5c/s to 60 c/s then $10g$ from 60 c/s to 500 c/s *Endurance*. 10 hr at resonant frequencies for $Q = 3$. V2 as for (i) except that *Endurance* is for 144 hr V3 *5* c/s to *5,000* c/s *Resonance Test* $3{\cdot}5\pi$ in./sec from 5 c/s. to $12\frac{1}{2}$ c/s and $10g$ from $12\frac{1}{2}$ c/s to 5,000 c/s *Functional* 30 c/s to 100 c/s 6π in./sec, then $30g$ from 100 c/s to 5,000 c/s

The Radio Industry Council specifications are private specifications published for the use of the radio industry. British Standards Institution general specifications are available and others are issued on individual components.

International Electrotechnical Commission (I.E.C.) specifications are also now being published.

R.I.C. GENERAL SPECIFICATIONS

RIC 1000/A: Choice of materials for radio and other electronic equipment and other components therein.

RIC 100/B: Choice of finishes for radio and other electronic equipment and other components therein.

RIC 1000/C: Standard colour coding for connections on radio and electronic equipment (other than domestic radio and television).

These are obtainable from the Radio Industry Council, 59 Russell Square, London, W.C.1.

R.C.S.C. AND DEFENCE SPECIFICATIONS GENERAL SPECIFICATIONS

DEF 5001: General specification and type-approved procedure for electronic components.

RCG 4: Guide to approved standard components.

DEF 5011: Specification for climatic and durability testing of Service electronic components.

DEF 5012: Guide to the climatic and durability testing of Service electronic components.

These are obtainable from The Radio Components Standardization Committee, 77–91 New Oxford Street, London, W.C.1. or from Her Majesty's Stationery Office (H.M.S.O.), York House, Kingsway, London, W.C.2.

B.S.I. General Specification

B.S. 2011 : 1954. Climatic and durability tests for components for radio and basic electronic equipment.

B.S.I. specifications are obtainable from the British Standards Institution, British Standards House, 2 Park Street, London, W.1.

I.E.C. General Specifications

No. 68: Basic climatic and mechanical robustness testing procedure for components for radio-communication.

This is obtainable from the International Electrotechnical Commission, Central Office, 39, Route de Malagnou, Geneva (or through the B.S.I.)

In addition to the general specifications given above, specifications covering specific components are also published. Those dealing with fixed capacitors are listed on p. 34.

British Component Date Codes

Manufacturers of electronic components bearing Joint Service Catalogue numbers are normally supplied with a three-letter code mark for marking their products. The individual component specifications detail the component markings required. In addition, Service components are normally marked with a date code to indicate the year and month of manufacture, as follows.

The *first* letter represents the year, where A means 1945, B means 1946, etc. The *second* letter represents the month, where A means January, B means February, etc.

As an example, XYZ/GD means Messrs. XYZ, 1951, April. Letters I and O are omitted; hence

J = 1953	A = January	G = July
K = 1954	B = February	H = August
L = 1955	C = March	J = September
M = 1956	D = April	K = October
N = 1957	E = May	L = November
P = 1958	F = June	M = December

CHAPTER 2

GENERAL INFORMATION ON FIXED CAPACITORS

CAPACITANCE

CAPACITANCE is present between any two adjacent conductors. A capacitor consists basically of two parallel metal plates separated by a dielectric material, such as air, gas, paper, ceramic, or an oxide film, etc. When a voltage is applied across the plates the capacitor will become charged and the amount of charge will depend mainly on the voltage. The capacitance of the capacitor is the ratio of the charge acquired to the voltage applied, or

$$C = Q/V$$

where Q = charge in coulombs (or ampere-seconds),

V = voltage in volts,

C = capacitance in farads.

The farad is the unit of capacitance and a capacitor has a capacitance of one farad if its potential rises by one volt when it receives a charge of one coulomb. This unit is inconveniently large for practical usage and the submultiples microfarad (μF one millionth of a farad) and a micromicrofarad ($\mu\mu$F) or picofarad (pF—one million millionth of a farad) are normally used.

The energy of the charge is stored up as electrostatic energy in the dielectric and is equal to $CV^2/2$. If this energy is absorbed at a uniform rate over a time t the power required is

$$P_{av} = \tfrac{1}{2} CV^2/t$$

where P_{av} = average power in watts,

C = capacitance in farads,

V = voltage in volts,

t = time in seconds.

Under a.c. conditions the rate at which energy is supplied to and returned by the capacitor is

$$P_{av} = 2\pi f C V^2$$

where f = frequency in cycles per second,

V = r.m.s. voltage.

When a direct voltage is applied to a capacitor, the electric field within the dielectric is displaced and the bound electric charges are polarized or displaced from their normal position of equilibrium. Work is therefore done in charging the capacitor. The work done in joules (or watt-seconds), which is available as stored potential energy, is

$$J = \tfrac{1}{2}QV, \text{ or } \tfrac{1}{2}CV^2, \text{ or } Q^2/2C$$

where J = energy in joules (or watt-seconds),

C = capacitance in farads,

V = voltage in volts,

Q = charge in coulombs (or ampere-seconds).

The fundamental formula for the capacitance of two flat parallel plates separated by a dielectric material is

$$C = (\varepsilon A \times 10^{12})/(4\pi d \times 9 \times 10^{11})$$

which becomes $C = 0{\cdot}0885\varepsilon A/d$

where C = capacitance in picofarads (pF),

ε = permittivity, or dielectric constant,*

A = area of one plate in square centimetres,

d = distance between plates in centimetres.

When more than one plate is used $(N - 1)$ is added to the top line, where N is the number of plates. Due to edge and fringe effects, this formula is not strictly true; the capacitance should be slightly higher and the following corrections should therefore be added to the plate dimensions—

For straight edges . .	add $0{\cdot}44\,d$ to the sides
For circular edges . .	add $0{\cdot}11\,d$ to the radius

The equivalent circuit of a capacitor may be represented as in Fig. 2.1,

where C = capacitance of capacitor,

R_s = resistance due to leads, plates and contacts,

R_p = resistance due to the dielectric and case material,

L = inductance of leads and plates of the capacitor.

* The recommended symbol (B.S. 1991 : 1954) for permittivity, ε (Greek epsilon) will be used throughout this book. The symbol κ (Greek kappa) was formerly used for this quantity and has survived in capacitor work, together with the contraction "high-k" for "high permittivity."

The behaviour of the capacitor at various frequencies is described later in this chapter (p. 25). It is important to remember that capacitance is never constant, except under certain fixed conditions. It changes with temperature, frequency and age, and the capacitance

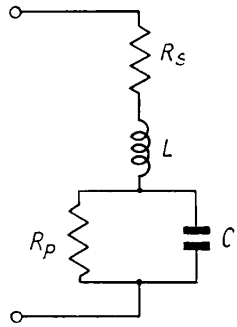


FIG. 2.1. EQUIVALENT CIRCUIT OF A CAPACITOR

value marked on any capacitor strictly applies only at room temperature and at low frequencies.

CHARACTERISTICS OF DIELECTRIC MATERIALS AND CAPACITORS

Dielectric materials used for radio and electronic capacitors can be grouped into the following five main classes—

(1) Mica, glass, low-loss ceramic, etc.	Used for capacitors from a few pF to a few hundred pF.
(2) High-permittivity ceramic	Used for capacitors from a few hundred pF to a few tens of thousands of pF.
(3) Paper and metallized paper	Used for capacitors from a few thousand pF up to some μF.
(4) Electrolytic (oxide film)	Used for capacitors from a few μF to many μF.
(5) Dielectrics such as polystyrene, polythene, polytetrafluorethylene, etc.	Range of use from a few hundred pF to some μF.

Many factors affect the dielectric properties of a material when it is used in a capacitor, among them being the permittivity, power factor, leakage current, dielectric absorption, dielectric strength and operating temperature, and these are discussed briefly below.

Permittivity (Dielectric Constant)

The permittivity, dielectric constant, or specific inductive capacity of any material used as a dielectric is equal to the ratio of the capacitance of a capacitor using the material as a dielectric, to the capacitance of the same capacitor using vacuum as a dielectric. The permittivity of dry air is approximately equal to one. A capacitor with solid or liquid dielectric of higher permittivity than air or vacuum can therefore store ε times as much energy for equal voltage applied across the capacitor plates. A few typical figures for capacitor dielectrics are—

	Permittivity (ε)
Vacuum	1·0
Dry air	1·00059
Polythene, polystyrene, etc.	2·0 to 3·0
Impregnated paper	4·0 to 6·0
Glass and mica	4·0 to 7·0
Aluminium oxide (anodic film)	7·0 to 9·0
Ceramic (magnesium titanate, etc.)	Up to 20
Tantalum oxide (anodic film)	27
Ceramic (titania)	80 to 100
Ceramic (high-ε)*	1,000 upwards

Dielectrics can be classified in two main groups—polar and non-polar materials. Polar materials have a permanent unbalance in the electric charges within the molecular structure. The dipoles within the structure consist of molecules whose ends are oppositely charged. These dipoles therefore tend to align themselves in the presence of an alternating electric field (if the frequency is not too high). The resultant oscillation causes a large loss at certain frequencies and at certain temperatures.

In non-polar materials the electric charges within the molecular structure are balanced and the dipoles do not rotate under applied fields, although they may distort. No sharp loss-peaks with frequency and temperature therefore exist. Polyvinylchloride (P.V.C.) is an example of a polar material, having a permittivity of 10 at low frequencies, falling to 3·0 or 4·0 at a few megacycles per second, whilst polystyrene is an example of a non-polar material, having a permittivity of approximately 2·5 both for direct current and for alternating currents up to many thousands of megacycles per second.

An exceptional material having special properties is high-permittivity ceramic, which is a non-polar material in that it maintains its permittivity for frequencies up to many thousands of megacycles per second, but has very high induced polarization effects. Under voltage stress, the molecular structure distorts to such an extent that it becomes

* The high permittivity in high-ε ceramic capacitors comes from the fact that the electric charges in the molecular structure of the material are very loosely bound and can move almost freely under the polarizing voltage, resulting in high total capacitance.

extremely sensitive to temperature, mechanical pressure and applied voltage. Under these circumstances, the permittivity becomes very high.

Losses in Dielectric Materials

Losses occur due to current leakage, dielectric absorption, etc., depending on the frequency of operation. For a good non-polar dielectric the curve relating loss with frequency takes the approximate shape

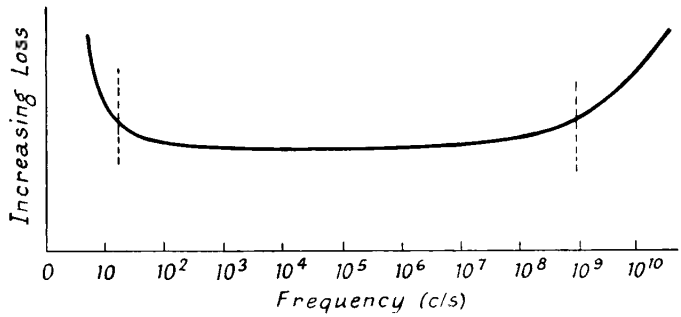


Fig. 2.2. Loss/Frequency Curve for a Non-polar Dielectric

given in Fig. 2.2. For a polar material the loss/frequency curve may be shown approximately as in Fig. 2.3.

The variation of permittivity with frequency is negligible so long as

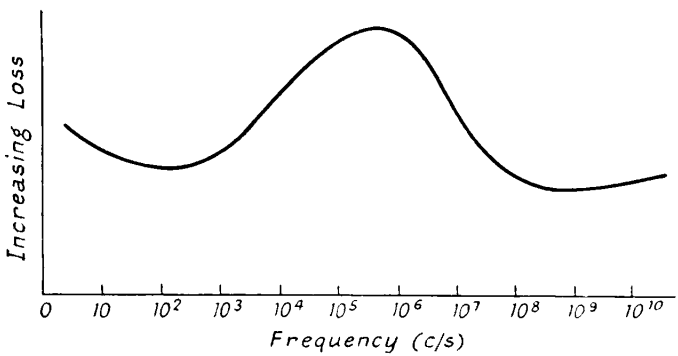


Fig. 2.3. Loss/Frequency Curve for a Polar Dielectric

the loss is low. Increased losses occur when the process of alignment cannot be completed, owing to molecular collisions, and in these regions there is a fall in permittivity. Viscous drag in the molecular structure limits the frequency at which full alignment can be carried out. If the

applied frequency is comparable with the limiting frequency losses will become high.

Equivalent circuits showing series and parallel loss resistance can be given, but are greatly dependent on the system of measurement at any particular frequency. The important criterion is the ratio

$$\frac{\text{power wasted per cycle}}{\text{power stored per cycle}}$$

This is the power factor of the material and for good dielectrics it is independent of frequency.

Power factor, phase angle and phase difference are defined as shown in Fig. 2.4.

When alternating current flows in a capacitor, the current leads the voltage by a little less than the theoretical 90° (angle ϕ in Fig. 2.4).

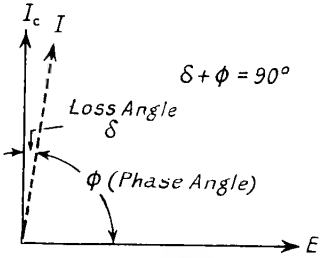


FIG. 2.4. VECTOR DIAGRAM FOR CAPACITOR

This is the phase angle, and the complement of this angle (δ) is termed the loss angle. The cosine of the phase angle or sine of the loss angle is the power factor. The dielectric loss is therefore $EI \cos \phi$, or $EI \sin \delta$. The loss angle is normally so small that tan δ can be taken as sin δ: it is more convenient to use tan δ, rather than sin δ or cos ϕ, as it is easier to measure. In a perfect capacitor with no dielectric loss $\delta = 0$. The power factor is

$$\cos \phi = 2\pi f RC \times 10^{-9}$$

where f = frequency in kilocycles per second,

R = equivalent series resistance in ohms,

C = capacitance in micromicrofarads.

The power factor can also be represented as the ratio of the power loss in the dielectric to the product of the applied voltage and current

i.e.
$$\frac{\text{total power loss in watts}}{\text{volts (r.m.s.) applied} \times \text{amperes (r.m.s.) flowing}}$$

The power factor therefore can be calculated from

$$\cos \phi = P \times 10^6/2\pi fCE^2$$

where P = total power loss in watts,
C = capacitance in microfarads,
E = voltage in volts,
f = frequency in cycles/second.

The Q-factor of a capacitor is the reciprocal of the power factor. It may alternatively be defined as the ratio of the pure reactance to the effective resistance.

Dielectric Absorption

If a capacitor were completely free from dielectric absorption the initial charging or polarization current when connected to a d.c. supply would be

$$i \quad (E/R)e^{-t/CR}$$

where i = current flowing after a time t,
E = applied voltage,
R = capacitor series resistance,

and the polarization current would die off asymptotically to zero. If R is small, this takes place in a very short time and the capacitor is completely charged. With all solid-dielectric capacitors it is found that, after a fully charged capacitor is momentarily discharged and left open circuited for some time, a new charge accumulates within the capacitor, because some of the original charge has been "absorbed" by the dielectric. This phenomenon is known as dielectric absorption. A time lag is thus introduced in the rate of charging and of discharging the capacitor.

Dielectric absorption is due to the finite time taken to displace the bound charges in the dielectric from their normal positions because of the viscous forces which resist their motion. Polarization time varies with different dielectrics—the polarization may be almost instantaneous or it may take many hours. Even within the same dielectric a few electrons or ions only become free to move after a period which may be seconds or even days. The effect is exceedingly complex and, for example, in the case of an impregnated-paper capacitor, the polarization times of paper and of impregnant are different. There are, in addition, many types of polarization which must be taken into account.

The effect of dielectric absorption is to reduce the capacitance as the frequency of operation is increased and also to cause unwanted time delays in certain pulse circuits or in circuits requiring rapid charge and discharge characteristics.

Leakage Currents and *RC* Products of Capacitors

Losses due to leakage currents when a capacitor is being used on d.c. prevent indefinite storage capacity being realized, and the charge acquired will leak away once the source is removed. The time constant, i.e. the time in which the charge leaks away to 1/e, or 36·8 per cent, of its initial value is given by RC, where R is the leakage, or insulation, resistance and C is the capacitance. Thus another name for the time constant of a capacitor is "*RC* product."* If R is measured in megohms* and C in microfarads the time constant is in seconds. This can also be expressed as megohm-microfarads or as ohm-farads. Some typical time constants for various dielectrics used in capacitors are

Polystyrene	Several days
Impregnated paper	Several hours
Tantalum-pellet electrolytic capacitors .	One or two hours
High-permittivity capacitors (ceramic) .	Several minutes
Plain-foil electrolytic capacitors . .	Several seconds

The variation of *RC* product for some typical capacitor dielectric films is shown in Fig. 2.5.

It should be borne in mind that below capacitance values of about 0·1 μF, the *RC* product is generally determined by the structure, leakage paths, etc., of the capacitor assembly itself rather than the dielectric material. Leakage current increases with increase of temperature (roughly exponentially). In good dielectrics at room temperature it is too small to measure, but at higher temperatures the current may become appreciable, even in good dielectrics.

Insulation Resistance

The insulation resistance of a dielectric material may be measured in terms of surface resistivity in ohms or megohms, or as volume resistivity in ohm-centimetres. Surface and volume resistivities are measured using apparatus similar to that shown in Fig. 2.6.

To measure surface resistivity the specimen is mounted in mercury and a p.d. of 500 V (d.c.) is applied across the inner and outer metal rings with mercury electrodes to the top surface. Typical resistivities for some good dielectrics measured in this way (to B.S.771 : 1954) are given in Table 2.1.

The *RC* product, in ohm-farads, is often quoted (*see* paper-dielectric capacitors), as the insulation resistance varies with capacitance, particularly in the higher capacitance values. Another object in quoting this quantity is that it is equal to the product of resistivity

* In the literature the whole product is often called "insulation resistance."

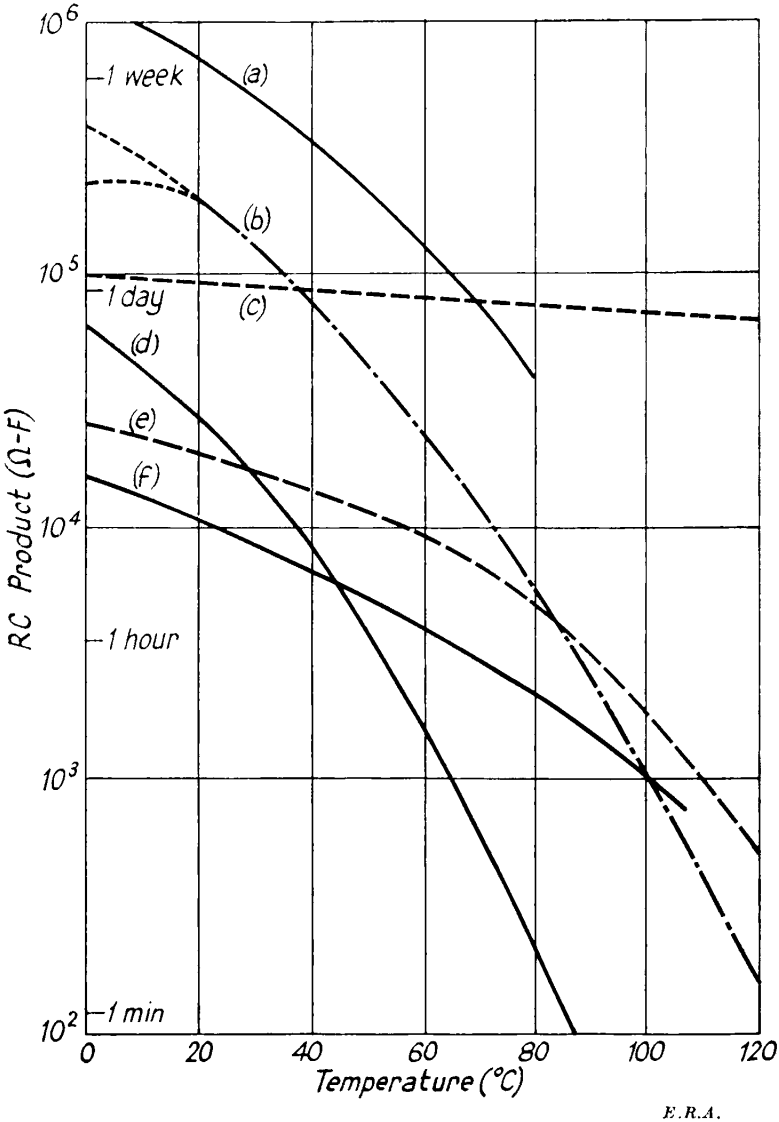


FIG. 2.5. *RC*-PRODUCT/TEMPERATURE CHARACTERISTICS OF VARIOUS FILM-FORMING DIELECTRICS

(*a*) Polystyrene film
(*b*) Polyethylene terephthalate (Melinex) film
(*c*) P.T.F.E. film
(*d*) Kraft paper and oil
(*e*) Aluminium oxide anodic film (experimental dry type)
(*f*) Mica

and permittivity, and is therefore independent of the dimensions of the dielectric.

Volume resistivity is measured similarly between the top and bottom surfaces, as shown on the left side of Fig. 2.6. Typical figures for

TABLE 2.1

Dielectric	Surface Resistivity (Ω)	Volume Resistivity (Ω-cm)
Polythene	4×10^{14}	10^{19}–10^{20}
Polystyrene	10^{16}	10^{17}–10^{19}
Polytetrafluoroethylene (P.T.F.E.)	$3{\cdot}5 \times 10^{13}$	10^{16}
Polyethylene terephthalate (Terylene or Melinex)	10^{13}	10^{13}

volume resistivities are shown in Table 2.1. It is important to remember that the insulation resistance of good dielectrics in a capacitor (glass, mica, etc.) may be reduced by any encasing material having a lower insulation resistance, such as the phenol resins, particularly under

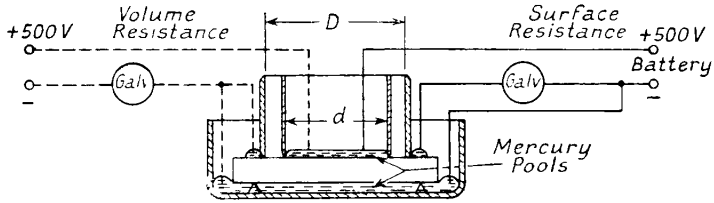


FIG. 2.6. TYPICAL ARRANGEMENT OF APPARATUS FOR SURFACE AND VOLUME RESISTIVITY TEST

conditions of high humidity or temperature. Some measurements on insulation resistance for typical capacitors at high temperatures are given on pp. 23 and 24.

THE INSULATION RESISTANCE OF FIXED CAPACTITORS

Methods of measurement of insulation resistance of dielectric materials have been described in the previous section, but the insulation resistance of the assembled capacitor is important in circuit use. The insulation resistance of any capacitor will be lowered in the presence of high humidity (unless it is sealed) and when operated in high ambient temperatures (whether sealed or not).

For perfectly sealed capacitors used under conditions of high humidity there should be no deterioration, but for imperfectly sealed capacitors the drop in insulation resistance will be roughly inversely proportional

to the effectiveness of the sealing. Unsealed capacitors will show a large and rapid drop in insulation resistance under these conditions.

Under high-temperature conditions the fall in insulation resistance for most capacitors is given approximately by the formula

$$R_T = R_t/e^{K(T-t)}$$

where R_T = insulation resistance at high temperature T,

R_t = insulation resistance at low temperature t,

e = base of Napierian logs (2·718),

K = a constant, as described below.

For both impregnated-paper and metallized-paper capacitors K is taken as 0·1. For mineral jelly impregnation the insulation resistance drops approximately to half its value for every 7°C rise in temperature corresponding to this value of K, and for oil impregnation it drops by approximately half for every 10°C rise in temperature. This becomes more important for the larger values of capacitors.

For mica and medium-permittivity ceramic capacitors K is taken as 0·05. As this constant is small it is often disregarded under normal operating conditions.

The sets of curves given in Figs. 2.7, 2.8 and 2.9 shows the results of measurements taken on typical impregnated-paper, metallized-paper, mica and ceramic capacitors. In each case the insulation resistance was measured at room temperature, at 70°C, at 85°C, at 100°C and at room temperature again. As waxed mica capacitors would not withstand temperatures of 70°C and above without the wax melting, this was removed for the purpose of these measurements.

All insulation resistance measurements are in megohms at 500 V d.c., with the exception of the metallized-paper types. These capacitors were tested at their working voltage with a 10-kΩ resistor in series, as is normal practice.

It will be seen from the curves that it is possible for the insulation resistance of a rectangular metal-cased impregnated-paper capacitor to fall to a few tens of megohms at a temperature of 100°C, whilst the tubular types (having a higher initial insulation resistance) may fall to a few hundred megohms at the same temperature. The fall in insulation resistance of mica capacitors depends greatly on the material in which the capacitor is encased. In general, the insulation resistance of ceramic capacitors does not fall below a few thousand megohms.

Dielectric Strength

The ultimate dielectric strength of a material is determined by the voltage at which it breaks down. The stress in kilovolts per inch (or

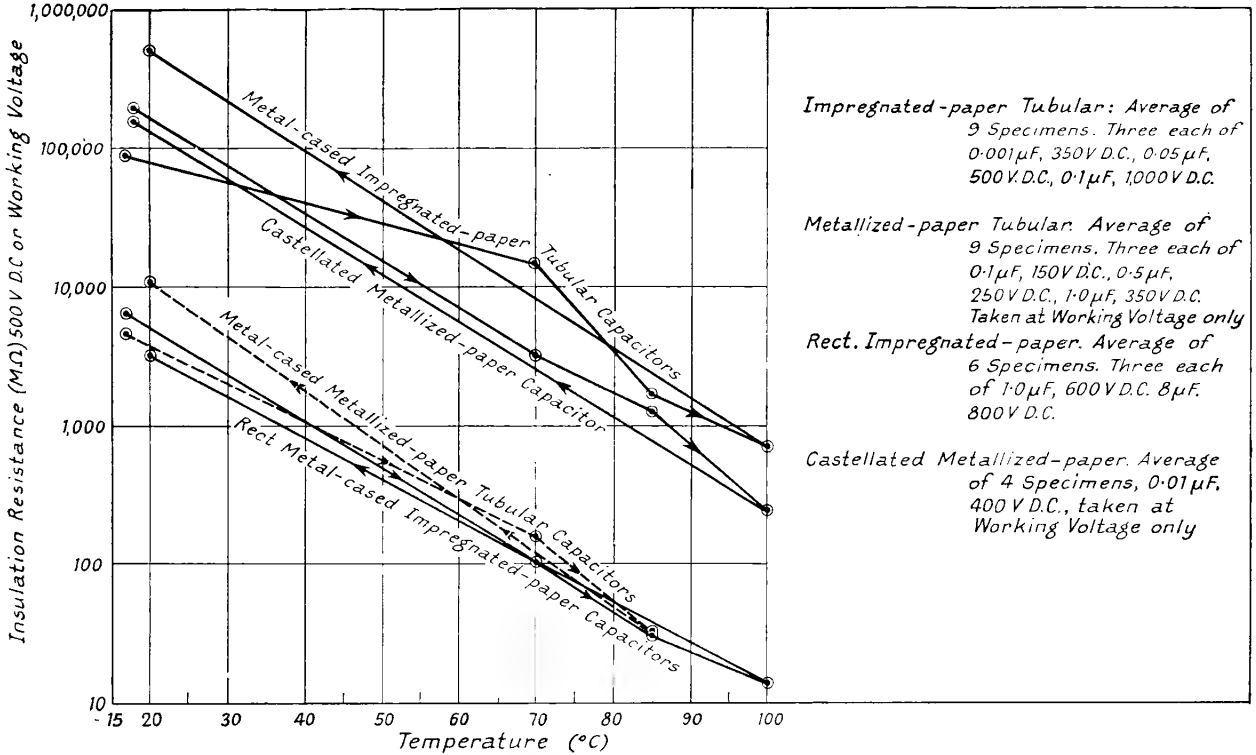

Insulation Resistance (MΩ) 500 V D.C or Working Voltage
1,000,000
100,000
10,000
1,000
100
10
15
20
30
40
50
60
70
80
90
100
Temperature (°C)
Metal-cased Impregnated-paper Tubular Capacitors
Castellated Metallized-paper Capacitor
Metal-cased Metallized-paper Tubular Capacitors
Rect Metal-cased Impregnated-paper Capacitors
Impregnated-paper Tubular: Average of 9 Specimens. Three each of 0·001 μF, 350 V D.C., 0·05 μF, 500 V.D.C., 0·1 μF, 1,000 V D.C.
Metallized-paper Tubular: Average of 9 Specimens. Three each of 0·1 μF, 150 V D.C., 0·5 μF, 250 V D.C., 1·0 μF, 350 V D.C. Taken at Working Voltage only
Rect. Impregnated-paper. Average of 6 Specimens. Three each of 1·0 μF, 600 V D.C. 8 μF. 800 V D.C.
Castellated Metallized-paper. Average of 4 Specimens, 0·01 μF. 400 V D.C., taken at Working Voltage only

FIG. 2.7. INSULATION RESISTANCE OF PAPER CAPACITORS

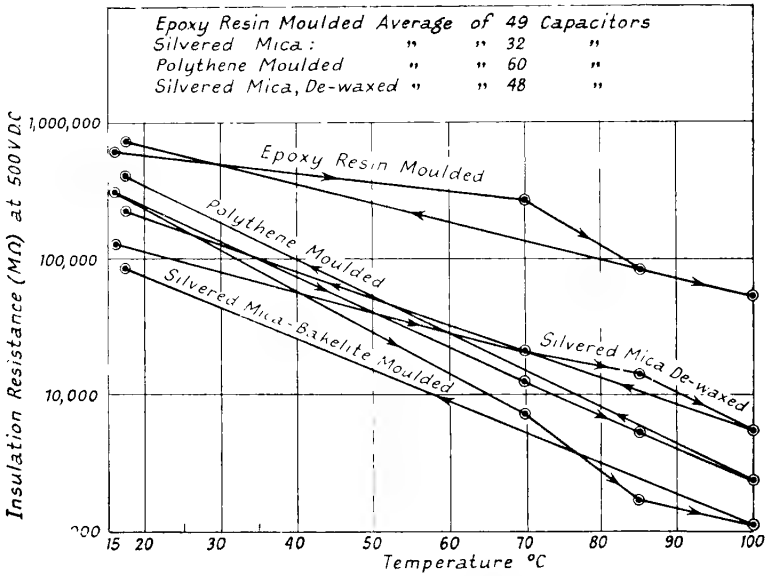

Epoxy Resin Moulded Average of 49 Capacitors
Silvered Mica : " " 32 "
Polythene Moulded " " 60 "
Silvered Mica, De-waxed " " 48 "
Insulation Resistance (MΩ) at 500V D.C
1,000,000
100,000
10,000
Epoxy Resin Moulded
Polythene Moulded
Silvered Mica-Bakelite Moulded
Silvered Mica De-waxed
15 20 30 40 50 60 70 80 90 100
Temperature °C

FIG. 2.8. INSULATION RESISTANCE OF SILVERED-MICA CAPACITORS

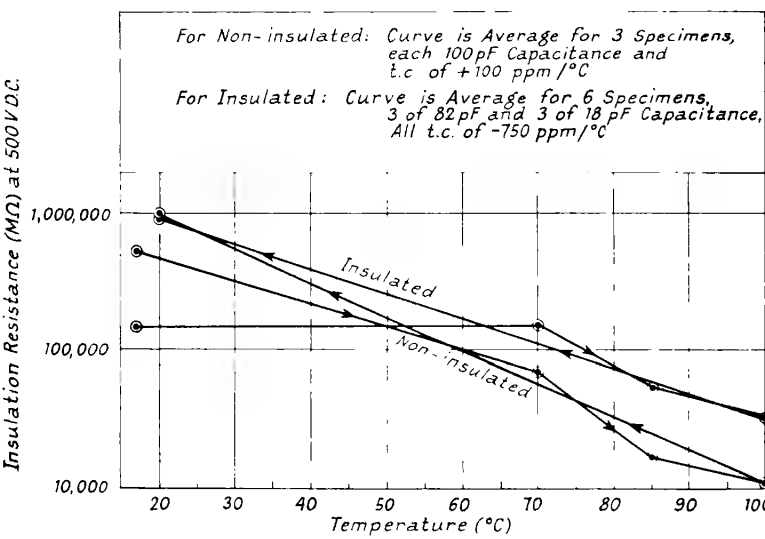

For Non-insulated: Curve is Average for 3 Specimens, each 100pF Capacitance and t.c of +100 ppm/°C
For Insulated: Curve is Average for 6 Specimens, 3 of 82pF and 3 of 18pF Capacitance, All t.c. of -750 ppm/°C
Insulation Resistance (MΩ) at 500V D.C.
1,000,000
100,000
10,000
Insulated
Non-insulated
20 30 40 50 60 70 80 90 100
Temperature (°C)

FIG. 2.9. INSULATION RESISTANCE OF TUBULAR CERAMIC CAPACITORS

volts per mil), at which this occurs depends on the thickness of the material, the temperature, the frequency and the waveform of the testing voltage, and the method of application, etc., and therefore comparisons between different materials should ideally be made on specimens equal in thickness and under identical conditions of measurement. The ultimate dielectric strength is measured by applying increasing voltage through electrodes fitted with guard rings to a specimen with recessed surfaces (to ensure that the region of maximum stress shall be as uniform as possible). Preparation of the specimens is important and their previous histories should be known. Dielectric-strength figures for most capacitor dielectrics are given in Tables 2.2 and 2.3 (pp. 30 and 32).

A practical limit to the dielectric strength of a material which is convenient to use is the *discharge inception voltage*, above which progressive breakdown occurs. This is usually much lower than the ultimate dielectric strength for short applications of voltage. Above the discharge inception voltage, a form of corona is created by the discharges and progressive deterioration takes place. It is an advantage that tests for inception discharge voltage are usually non-destructive tests, as corona produces "noise" which can be detected and measured.

The dielectric strength of a material is always reduced when it is operated at high temperatures or if moisture is present. Few materials are completely homogeneous and breakdown may take the form of current leak along certain small paths through the material; these become heated and cause rapid deterioration or flashover along the surface and permanent carbonization of the surface of organic materials. Inorganic materials such as glass, ceramic and mica are usually resistant to this form of breakdown. The time for which the voltage is applied is important; most dielectrics will withstand a much higher voltage for brief periods. With increasing frequency the dielectric strength is reduced, particularly at radio frequencies, depending on the power factor, etc., of the material.

The Effect of Frequency on Dielectric Materials and Capacitor Assemblies

At very low frequencies and also at very high frequencies there is an increase of loss which sets a limit to the practical use of a capacitor with any given dielectric. At very low frequencies various forms of leakage in the dielectric material have time to become apparent, such as d.c. leakage currents and long time-constant effects, which have no effect at high frequencies. At very high frequencies some of the processes contributing to dielectric polarization do not have time to become effective and therefore cause loss. These losses might be simply and approximately represented as in Fig. 2.10.

At very low frequencies the circuit is entirely resistive, all the current passing through the shunt resistance (d.c. leakage resistance, etc.). At very high frequencies the current passes through the capacitance C but all the voltage is dropped across the series resistance and again the

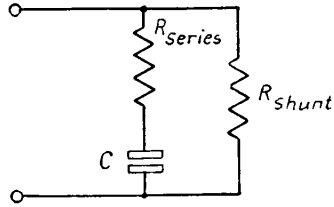


FIG. 2.10. LOSSES IN A CAPACITOR

circuit is lossy. The series resistance may consist of the resistance of the capacitor leads, the silvering (in the case of silvered mica or ceramic capacitors), contact resistances, etc., in the capacitor assembly itself. These limit the upper frequency independently of the dielectric material used. Similarly, leakage across the case containing the dielectric may limit the lower frequency so that not all the useful range of the dielectric itself may be realized.

The chart in Fig. 2.11 shows the approximate usable frequency ranges for capacitors with various dielectric materials. The construction of the capacitor assembly will affect the frequency coverage to some extent, so that the chart should be regarded as a guide only.

THE IMPEDANCE OF A CAPACITOR

The current in a capacitor when an alternating voltage is applied is given by

$$I = 2\pi fCV \text{ amperes}$$

where C = capacitance in farads,

V = voltage in volts,

f = frequency in cycles per second,

and the reactance is given by

$$X_c = -1/2\pi fC \text{ ohms}$$

An ideal capacitor would have entirely negative reactance but the losses, described previously, due to dielectric, case and leads, preclude this. In addition, inductance is also present in varying amounts and therefore as the frequency is increased the inductive or positive reactance increases, and above a critical frequency the capacitor

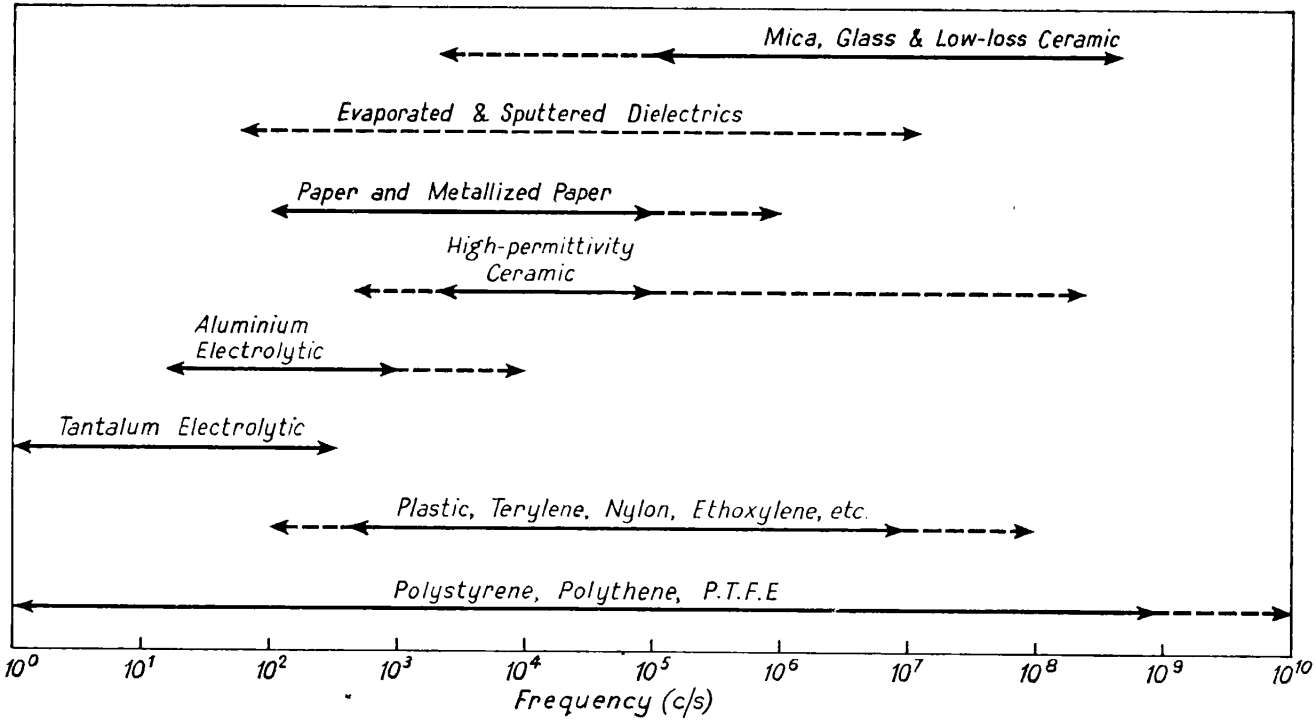

Mica, Glass & Low-loss Ceramic
Evaporated & Sputtered Dielectrics
Paper and Metallized Paper
High-permittivity Ceramic
Aluminium Electrolytic
Tantalum Electrolytic
Plastic, Terylene, Nylon, Ethoxylene, etc.
Polystyrene, Polythene, P.T.F.E
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
Frequency (c/s)

FIG. 2.11. FREQUENCY COVERAGE OF DIFFERENT CLASSES OF CAPACITOR

will behave as an inductor. At the resonant frequency the impedance of the capacitor is controlled by its effective resistance, which in turn is made up of the losses described. Every capacitor will resonate at some given frequency (depending on its construction) and, having inductance and resistance, will exhibit a complex impedance, capacitative in one range of frequencies, resistive in another, and inductive in still another. The variation of impedance with frequency of a typical paper-dielectric capacitor is shown in Fig. 4.7 (p. 89).

In order to contribute primarily capacitance to a system a capacitor should have its self-resonant frequency well above the range in which it is expected to be used. Leads to the capacitor will cause the self-resonant frequency to decrease. For example, if leads of 0·2 in. length are used, the self-resonance of a 100-pF capacitor will be about 170 Mc/s, rather than 285 Mc/s for the body alone. In contrast, high-quality competitive 100-pF capacitors with the same lead length, but having different construction and a case, will have a self-resonance of about 145 Mc/s.

Three effects are involved in impairing the desired short-circuiting effect for very high frequencies and, even more so, ultra-high frequencies—

(1) Undesired lead inductances.
(2) Resonance effects within the dielectric.
(3) Coupling between input and output.

The first case is exemplified in standard disc capacitors with wire leads; for instance, a standard 5,000-pF disc capacitor becomes inductive even for very short leads above 10 to 20 Mc/s.

Feed-through capacitors eliminate these lead inductances, undesirable in the shunt branch, but they possess cavity resonances in the dielectric body. In case of parallel resonances, the capacitor becomes the opposite of what is desired. By changing the configuration of the feed-through capacitor from a cylindrical (tubular) to a discoidal structure, the detrimental parallel resonances can be shifted to much higher frequencies, although the same nominal capacitance applies in both cases.

Fig. 2.12 shows the variation of transfer impedance with frequency for a plain tubular, a tubular with external corrugated surface and a disc ceramic capacitor.

Microsecond Pulse Response of Large Capacitors

Using a pulse testing circuit which enables capacitors of the order of 1 μF and more to be charged in periods of 1 or 2 μs, the effective capacitance and resistance under these conditions can be assessed. Results are summarized below.

Foil type electrolytics retain a high capacitance under these conditions, though much less than their nominal, low-frequency values, and they are largely resistive.

Very large foil electrolytics may, however, be inductive—a feature which would perhaps be avoided by alterations to design.

High-ε types retain their value unimpaired, but they are at present too bulky to be useful. This difficulty could be overcome by using a thinner film.

Paper capacitors are suitable in design, but their frequency limit is approached, and a plastic, if it were available as a thin enough film, would be more suitable.

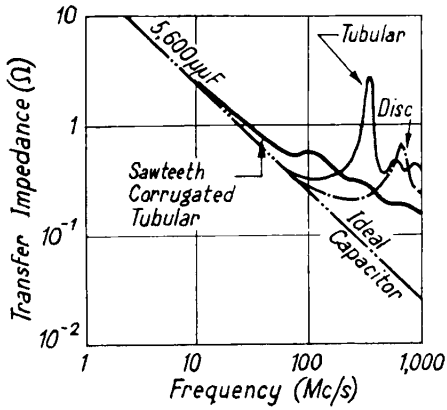


FIG. 2.12. TRANSFER-IMPEDANCE/FREQUENCY CHARACTERISTIC OF 5,600-pF PLAIN TUBULAR SAWTOOTH-CORRUGATED FEED-THROUGH CAPACITOR

TABLES OF PROPERTIES OF DIELECTRIC MATERIALS USED FOR CAPACITORS

Tables 2.2 and 2.3 give an indication of the main properties of most of the materials used as capacitor dielectrics. Most of the recently developed dielectric materials are included.

The most complete tables of properties of dielectric materials are those published by the Laboratory for Insulation Research, Boston, U.S.A., by Professor A. R. von Hippel and his associates. These tables are contained in the book *Dielectric Materials and Applications* (*see* Bibliography, p. 230).

As the loss/frequency curves for most good dielectrics are flat over most of the frequency band, rising at very low and very high frequencies (*see* Fig. 2.2) it is considered necessary to give only the

TABLE 2.2. PROPERTIES OF SOME CAPACITOR DIELECTRIC MATERIALS

Material	Loss (at room temperature)			Permittivity (over operating frequency range)	Dielectric strength (Volts per mil) (Breakdown)	Temperature limits (°C)		Remarks (and some (registered) Trade Names)
	Limiting frequency of operation		Power factor (Loss angle tan δ) at 1 kc/s					
	Approx. min.	Approx. max.				Approx. min.	Approx. max.	
1	2	3	4	5	6	7	8	9
Kraft paper (capacitor tissue)	Poor below 100 c/s (can be d.c.)	1 Mc/s	0·01 to 0·03	4·5	500 to 1,000 (depends on impregnant)	No limit but impregnant freezes	85 to 100	Capacitor properties depend greatly on impregnant
with mineral oil	—	—	0·0035	2·23	—	−55	105	Effect of various impregnants
with castor oil	—	—	0·007	4·7	—	−25	65	
with silicone oil	—	—	0·0035	2·6	—	- 60	125	
with polyisobutylene	—	—	0·003	2·2	—	−55	125	
with chloronapthalene	—	—	0·005	5·2	—	- 20	55	
with diphenyl	—	—	0·003	4·9	—	- 55	85	
Mica (Ruby)	Precision work 100 c/s (can be d.c.)	10,000 Mc/s	0·0005	7·0	1,000	No limit	+ 200	Properties vary according to source of origin
Ceramic (Low-permittivity types) Magnesium silicate	100 c/s*	10,000 Mc/s	0·001	5·4 to 7·0	200 to 300	No limit	+ 150 to 200	Steatite, Tempradex, Frequentex, etc.
(Medium-permittivity types) Titania Rutile (TiO_2)	500 c/s*	5,000 Mc/s	0·001	70 to 90	100 to 150	No limit	+ 120	Faradex, Condensa, (Has large temperature coefficient, approx. − 750 ppm/°C)†
(High-permittivity types) Titanate	1,000 c/s*	1,000 Mc/s	0·01	Approx. 1,000 to over 7,000	100	− 100	+ 120	Characteristics dependent on temperature. Sharp max. in permittivity at 120°C. Permittivity depends on volts. Below 120°C hysteresis occurs and loss dependent on volts. Other high-permittivity materials exist with different peaks

Glass (Soft lead-soda)	**200 c/s**	**10,000 Mc/s**	**0·001**	**6·5 to 6·8**	**< 500**	**No limit**	**+ 200**	
Glass (Hard, borosilicate)	**100 c/s**	**10,000 Mc/s**	**0·001**	**4·0**	**< 500**	**No limit**	**+ 200**	
Quartz (Fused)	100 c/s	>10,000 Mc/s	0·0002	3·8	1,000	No limit	+ 300	
Plastics Polyethylene	d.c.	10,000 Mc/s	0·0002	2·3	1,000	Becomes brittle − 40	+ 70	Polythene, Alkathene, Telcothene
Polystyrene film	**d.c.**	**10,000 Mc/s**	**0·0003**	**2·3**	**1,000**	**− 40**	**+ 65**	**Distrene, Lustron, Styron, Trolitul**
Polytetrafluoroethylene (P.T.F.E.) shaved film	d.c.	10,000 Mc/s	0·0001	2·0	1,000 to 2,000	− 60	+ 285	Fluon, Teflon
Polymonochlorotrifluoro-ethylene (P.C.T.F.E.) film	d.c.	10,000 Mc/s	0·01 to 0·05	2·3 to 2·8	3,000 to 5,000	− 195	+ 180	Kel-F, Hostaflon
Polyethylene terephthalate film	Poor between, say, 0·1 to 10 Mc/s		0·01 at l.f. 0·001 at h.f.	3·1	4,000 to 5,000	40	+ 130	Terylene or Melinex. Could replace paper at l.f.
Paraffin wax	d.c.	10,000 Mc/s	0·0001	2·2	1,000	No limit but hardens	60	Capacitor impregnant, coil potting, etc.
Liquid insulants Paraffin	d.c.	10,000 Mc/s	0·001	2.2	1,000	No limit but solidifies	50	Ozokerite (slightly plastic). Used for coil potting
Transformer oil	**d.c.**	**1 Mc/s**	**0·001**	**2·4**	**1,000**	**− 40**	**120**	
Silicone oil	**d.c.**	**10,000 Mc/s**	**0·0001**	**2·8**	**1,000**	**− 50**	**250**	
Nitro-benzene	(see remarks)	10,000 Mc/s	0·0005	40	50 to 1,000	Freezes at + 3 then low permittivity	150	Note high permittivity. Cannot be used on d.c. because of leakage. Has large negative temperature coefficient. Has specialized use as capacitor dielectric

* Can be d.c. but slow capacitance change possible.

† ppm/°C = parts per million per degree Centigrade.

TABLE 2.3. CHARACTERISTICS OF VARIOUS

Material	Usual Form	Method of Moulding	Permittivity (at 1 kc/s)	Power Factor (at 1 kc/s)	Breakdown Strength (volts/mil)
Phenol formaldehyde (P.F.)	Moulding powder; paper, cloth and glass laminated sheeting, rod and tubing. Usually brown or black in colour	Compression	4 to 7	0·01 to 0·2	250 to 400
Urea formaldehyde (U.F.)	Moulding powder, paper and cloth laminated sheeting. Full range of colours available	Compression	7 to 8	0·02 to 0·04	300 to 400
Melamine formaldehyde	Moulding powder. Usually grey-brown in colour. Laminated sheeting	Compression	6 to 9	0·015 to 0·036	300 to 400
Polymethyl-methacrylate	Moulding granules, sheeting. Transparent or coloured	Compression, injection blowing and extrusion	3 to 3·2	0·04	380 to 390
Cellulose acetate	Moulding powder, film and sheeting. Transparent and coloured	Compression, injection and extrusion	3·5 to 7	0·01 to 0·06	250 to 365
Polystyrene	Moulding granules, rod and film. Transparent or coloured	Compression, injection and extrusion	2·45 to 2·65	0·0001 to 0·0005	500 to 700
Polyvinylchloride (P.V.C.)	Sheeting, tubing and pastes. All colours. Rigid and flexible grades available	Injection, extrusion, casting, dipping and coating	6 to 7	0·012	400
Polyethylene	Moulding granules, rod and film. White greasy feeling	Injection and extrusion	2·3	0·0001 to 0·0002	1,000
Polytetrafluoro-ethylene (P.T.F.E.)	Moulding granules, film. White, greasy feeling	Dry pressing followed by heat curing	2·0	< 0·0001	480
Polychlortrifluoro-ethylene (P.C.T.F.E.)	Moulding granules, film. White, translucent	Injection, extrusion and compression	2·8	0·024	2,500
Polyamide	Moulding powder, film or monofilament. All colours. Horn-like appearance	Compression, injection and extrusion	3·6	0·02	300 to 400
Polyester	Liquid syrups. Usually clear or amber coloured. May be dyed all colours	Casting, pouring and impregnating (usually glass fabric)	3 to 5	0·01 to 0·05	250 to 450
Ethoxyline (Epoxy)	Powder or viscous liquids. Amber or brown in colour	Casting, pouring	4	0·03	320

Plastic Insulating Materials

Common Uses	(Registered) Trade Names	Remarks
Cabinets, knobs, valve holders and bases, terminal blocks, tag-boards, fuse holders, instrument cases, aerial mountings, etc.	Bakelite, Mouldrite, Nestorite, Elo, Paxolin, Tufnol, Pirtoid, Rockite, Beckacite, Delaron, Ashlam, etc.	The inclusion of fillers such as paper, cloth, mica, asbestos, nylon, etc., considerably modifies the properties. Special grades are available for electrical purposes; these possess low water absorption and high resistance to tracking
Cabinets, knobs, instrument cases, name plates, etc.	Bakelite, Mouldrite, Beetle, Rockite, etc.	Seldom used for electrical but extensively for decorative purposes
Plugs and sockets, switch parts, etc.	Melamine	Highly resistant to arcing and tracking
Transparent canopies, scales and radomes, etc.	Perspex, Diakon, Lucite, Plexiglass, etc.	Easily fabricated and bent into complex shapes
Cabinets, knobs, scales, etc.	Cellomold, Celastoid, Tenite, etc.	Non-inflammable film material
Coil formers, aerial insulators, r.f. plugs and sockets, capacitor film, etc.	Lustrex, Styron, Styroplas, Distrene, Trolitul, etc.	A high-quality electrical insulator and dielectric material, suffers from low heat resistance (about 65°C)
Wire coverings, sleeving, tubing, etc.	Welvic, Vinatex, Vinatube, Vinylite, Geon, Vibak, etc.	Properties considerably modified by included plasticizers. Some P.V.C. compounds are co-polymers with vinylidene, acetate, butyrate and other resins
R.f. cable dielectrics, plugs, sockets, aerial mounts and terminations, capacitor film, etc.	Polythene, Alkathene, Telcothene	A high-quality electrical insulator and dielectric material available in a variety of grades. Low-grade numbers should be used for maximum heat resistance. Many contain polyisobutylene as a plasticizer. Anti-oxidants are often included
R.f. cable dielectric, aerial mounts, etc.	Fluon, Teflon	The best plastic dielectric material discovered to date, withstands temperatures up to 250°C. Very difficult to mould into intricate shapes. No known adhesive will stick to it. Very expensive to produce
R.f. cables, aerial mounts	Kel-F, Hostaflon	Almost as good as P.T.F.E. but may be moulded by conventional methods. Very expensive to produce
Coil formers, etc.	Nylon	May be used at temperatures up to 135°C. Very tough and resistant to abrasion. High water absorption may produce unstable electrical and mechanical properties
Radomes, component protection, potted circuits	Marco, Paraplex, Laminac, Nuron, etc.	Polymerized by means of a catalyst and sometimes an accelerator. May be cured either at room or elevated temperatures. Properties are modified by fillers—mica, slate, glass, chalk, etc. being commonly used
Component protection, potted circuits, adhesives	Araldite, Epikote, etc.	Polymerized in conjunction with a hardener—usually an amine substance. Excellent adhesive properties to metal, glass, ceramic, etc. May be filled with mica, slate, sand, etc., to reduce thermal expansion

upper and lower limits of frequency for these good materials. In the tables, therefore, only these figures are given unless there are marked variations. The temperature limits over which the dielectrics can operate are also given, but it is emphasized that these figures are a guide only, as variations in composition, etc., may affect the working temperature ranges of the materials. As so many plastic materials have been developed, a separate table of properties for insulating plastic materials is given in Table 2.3, including some materials not employed as dielectrics but often encountered in electrical work.

FIXED CAPACITOR SPECIFICATIONS

There are two main sets of specifications in general use in the United Kingdom, those prepared by the Radio Components Standardization Committee (R.C.S.C.) for Service components, and those prepared by the Radio Industry Council (R.I.C.) for commercial components. Specifications are also available from the British Standards Institution (B.S.I.) and the International Electrotechnical Commission (I.E.C.).

R.C.S.C. Specifications*

Def. 5131: Specification for capacitors, fixed, paper-dielectric (d.c. rated).

Def. 5132: Specification for capacitors, fixed, mica-dielectric.

Def. 5133-1: Specification for capacitors, fixed, ceramic-dielectric, (normal permittivity).

Def. 5133-2: Specification for capacitors, fixed, ceramic-dielectric, (high permittivity).

Def. 5134-1: Specification for capacitors, fixed, electrolytic (not suitable for use below −25°C).

Def. 5134-2: Specification for capacitors, fixed, electrolytic (with tantalum electrode).

Def. 5136: Specification for capacitors, fixed, paper-dielectric, metallized (d.c. rated).

Def. 5137: Specification for capacitors, fixed, plastic-film dielectric (d.c. rated), suitable only for temperatures from −30°C to +60°C.

These are obtainable from H.M. Stationery Office, Kingsway, London, W.C.2.

RCS (Prov) 135: Capacitors, fixed, vitreous enamelled and glass dielectric.

RCG 130: Guide on capacitors, fixed.

These two documents are obtainable from The Radio Components Standardization Committee, 77–91 New Oxford Street, London, W.C.1.

* Shortly to be Def. 5138: General Specification excluding electrolytics, and Def. 5134A: General specification for electrolytic capacitors.

R.I.C. Specifications

RIC/131: Capacitors, fixed, paper-dielectric, tubular, foil.
RIC/132: Capacitors, fixed, mica-dielectric, stacked foil.
RIC/133: Capacitors, fixed, ceramic-dielectric, Grade 1.
RIC/134: Capacitors, fixed, electrolytic.
RIC/136: Capacitors, fixed, paper-dielectric, tubular, metallized.
RIC/137: Capacitors, fixed, mica-dielectric, metallized.

These are obtainable from The Radio Industry Council, 21 Tothill Street, London, S.W.1. They are private specifications and are published for use by the radio industry.

B.S.I. Specifications

Some of the specifications published by the British Standards Institution are similar to the R.C.S.C. specifications, but have reference numbers beginning with "2" instead of "5." Those published to date relating to fixed capacitors are as follows.

B.S. 2131: 1956. Fixed capacitors—paper (or material of equivalent performance) dielectric and metal foil types.
(This standard is being replaced by CT/TLE/8448, still in draft.)

B.S. 2133A. Fixed ceramic-dielectric capacitors Grade 1, for use in telecommunication and allied electronic equipment.
Part 1, 1960. General requirements and tests.

B.S. 2133B. Fixed ceramic-dielectric capacitors Grade 2, for use in telecommunication and allied electronic equipment.
Part 1, 1961. General requirements and tests.

B.S. 2134. Fixed electrolytic capacitors (aluminium electrodes) for use in telecommunication and allied electronic equipment.
Part 1, 1959. General requirements and tests.
Part 2, 1959. List of standard capacitors.

B.S. 2136. Fixed metallized-paper-dielectric capacitors for s.c. operation for use in telecommunication and allied electronic equipment.
Part 1, 1961. General requirements and tests.

Other B.S.I. specifications relating to fixed capacitors which are of interest are—

B.S. 698: 1956. Papers (unvarnished) for electrical purposes (excluding asbestos papers and those used in the manufacture of cable).
B.S. 613: 1955 (revised CR(ELE) 7123). Components and filter units for radio interference suppressor devices (excluding devices for traction, marine and other special equipment).

B.S. 2488 : 1954. Preferred values and associated tolerances for resistors and capacitors for telecommunication and allied electronic equipment.

B.S. 3347 : 1961. Capacitors for railway signalling track circuits.

B.S. 1650. Capacitors: Deals with paper-dielectric capacitors for connection to power frequency systems.

Part 1: 1950. Continuously rated capacitors (above 1 kVA).

B.S. 2067: 1953. Determination of power factor and permittivity of insulating materials (Hartshorn and Ward method).

B.S. 2488 : 1954. Preferred values and associated tolerances for resistors and capacitors for telecommunication equipment.

These specifications are all obtainable from The British Standards Institution, British Standards House, 2 Park Street, London W.1.

I.E.C. Specifications

Publication 63: Series of preferred values and their associated tolerances for resistors and capacitors.

Publication 80: Specification for fixed paper capacitors for direct current.

Publication 103: Recommendations for aluminium electrolytic capacitors for general purpose application.

Publication 108. Recommendations for ceramic dielectric capacitors Type 1.

Publication 116: Recommendations for receiver-type metallized mica capacitors for use in electronic equipment.

I.E.C. Specifications are published by The Central Office of the I.E.C., 39 Route de Malagnou, Geneva, Switzerland. They are obtainable in the United Kingdom from The British Standards Institution, British Standards House, 2 Park Street, London, W.1.

American Specifications

American specifications on fixed capacitors may be of interest and are given below.

There are two main sets of specifications in general use in the United States today: those prepared by the Department of Defense (the military series) for military electronic parts and those prepared by the Electronic Industries Association (EIA) for commercial electronic parts. (EIA was formerly the Radio, Electronic and Television Manufacturers Association (RETMA).) The Aircraft Industries Association (AIA) has issued a limited number of specifications, which are also available.

Department of Defense Specifications

MIL-C-5B: Capacitors, fixed, mica-dielectric.
MIL-C-20D: Capacitors, fixed, ceramic-dielectric (temperature compensating).
MIL-C-25A: Capacitors, fixed, paper-dielectric, d.c. (hermetically sealed in metallic cases).
MIL-C-62B: Capacitors, fixed, electrolytic (d.c. aluminium, dry-electrolytic, polarized).
MIL-C-91A: Capacitors, fixed, paper-dielectric (nonmetallic cases).
MIL-C-3871: Capacitors, fixed, electrolytic (a.c. dry-electrolytic, nonpolarized).
MIL-C-3965B: Capacitors, fixed, electrolytic (tantalum).
MIL-C-10950B: Capacitors, fixed, mica-dielectric, button styles.
MIL-C-110158B: Capacitors, fixed, ceramic-dielectric (general-purpose).
MIL-C-11272B: Capacitors, fixed, glass-dielectric.
MIL-C-21720A: Capacitors, fixed, solid electrolytic, tantalum.
MIL-C-18312B: Capacitors, fixed paper (or mylar) dielectric, metallized, d.c.
MIL-C-11693: Capacitors, feed-through, radio-interference reduction, paper-dielectric, a.c. and d.c. (hermetically sealed in metallic cases).
MIL-C-14157: Capacitors, fixed, paper-dielectric, d.c. high reliability (hermetically sealed in metallic cases).
MIL-C-18312: (Navy): Capacitors, fixed, paper-dielectric, metallized-paper construction, d.c. hermetically sealed in metallic cases.
MIL-C-19978 (Navy): Capacitors, fixed, plastic-dielectric.
MIL-C-21720 (Ships): Capacitors, fixed, solid-electrolyte, tantalum.

Except the Navy specifications, the above specifications are obtainable from the Armed Services Electro Standards Agency (ASESA), at Fort Monmouth, N.J.

Navy Department specifications are obtained from the Commanding Officer, Naval Aviation Supply Depot, 5801 Tabor Ave., Philadelphia 20, Pa.

EIA Specifications

REC-107A: Capacitors, fixed, ceramic-dielectric, classes 1 and 2. (1,000–75,000-V rating).
RS-171: Capacitors, fixed, ceramic-dielectric, high voltage, class 2.
RS-154: Capacitors, fixed, dry electrolytic, for general use.
TR-140: Capacitors, fixed, dry electrolytic, special quality.
RS-153: Capacitors, fixed, mica, moulded types.
TR-109: Capacitors, fixed, mica, potted types.

TR-113A: Capacitors, fixed, paper-dielectric, metal encased. d.c. applications.

RS-164: Capacitors, fixed, paper-dielectric, nonmetallic, tubular types.

These are obtainable from the Electronic Industries Association, Engineering Office, Room 650, 11 West 42d Street, New York 36, N.Y.

Fixed-capacitor Symbols

Symbols which have been agreed by the Electronics Glossary and Symbols Panel of the Central Radio Bureau and the Inter-Services Radio Circuits Symbols Committee, are given in Fig. 2.13.

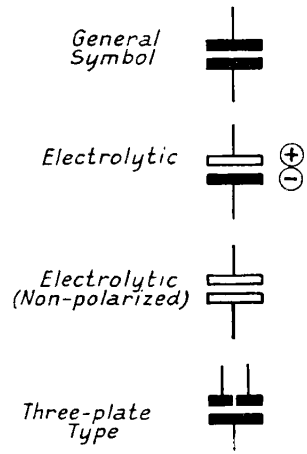


Fig. 2.13. Fixed-capacitor Symbols

Preferred or Standard Types and Values

Rationalized types and values agreed by the R.C.S.C. and R.I.C. are detailed in the R.C.S.C. and R.I.C. lists, and some of the B.S.I. and I.E.C. specifications already mentioned also give preferred lists.

Standard values for the smaller values of capacitors generally follow the resistor preferred values, i.e. 10, 22, 47 pF, etc., whilst those for the larger capacitances usually follow the geometrical progression series of values, i.e. 2, 4, 8, 16, 32 μF, etc.

BRITISH COLOUR CODES

Unless otherwise specified the colours used are those defined by the following British Standards (*see* B.S. Colour Card 381C: 1948).

412 Dark Brown	796 Dark Violet
538 Post Office Red	632 Dark Battleship Grey

557 Light Orange	443 Salmon Pink
355 Lemon	216 Eau-de-Nil
221 Brilliant Green	166 French Blue
101 Sky Blue	

Paper-dielectric Capacitors

Paper-dielectric capacitors are usually marked with their capacitance value, etc., on the case, as adequate space is usually available. British paper-dielectric capacitors using metallized paper ("metallized-paper capacitors") have either red sleeving or red printing to distinguish them from foil types.

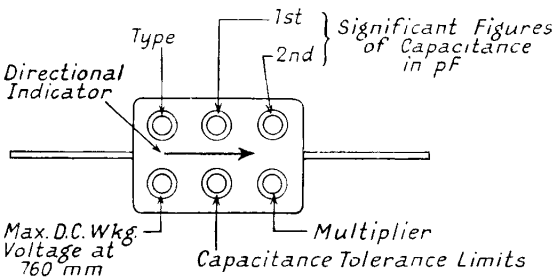


Fig. 2.14. British Mica Capacitor Colour Code

Mica-dielectric Capacitors

These capacitors are sometimes colour coded by a six-dot code to denote the capacitor characteristics. The dots are arranged in two rows of three with an arrow indicator to show in which direction the dots are to be read, as shown in Fig. 2.14.

The colour code used for the dots is given in Table 2.4.

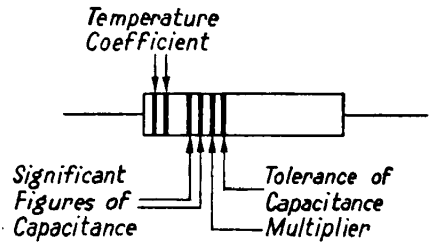


Fig. 2.15. British Ceramic Capacitor Colour Code

Ceramic-dielectric Capacitors

The standard colour code for ceramic capacitors is shown in Table 2.5 and an example is given in Fig. 2.15.

TABLE 2.4. BRITISH MICA CAPACITOR COLOUR CODE

Colour	Type*	Capacitance			Rating Volts at 760 mm Hg
		Nominal (pF)		Tolerance (%)	
		1st and 2nd Significant Figures	Multiplier		
Black	—	0	1	—	—
Brown	—	1	10	—	—
Red	Metallized	2	100	± 2	350
Orange	—	3	1,000	—	—
Yellow	—	4	—	—	—
Green	Foil	5	—	—	750
Blue	—	6	—	—	—
Violet	—	7	—	—	—
Grey	—	8	—	—	—
White	—	9	—	—	2,000
Gold	—	—	0·1	± 5	—
Silver	—	—	0·01	± 10	—
Black (or no colour)	—	—	—	± 20	—

* Coloured flecking may be used in the moulding to differentiate between metallized and foil types as an alternative to colouring the first dot.

TABLE 2.5. BRITISH CERAMIC CAPACITOR COLOUR CODE

Colour (B.S. 381C Number)	Temperature coefficient		Capacitance (pF)		Tolerance values, fourth colour	
	First colour, (ppm/°C)	Second colour, multiplier	First and second colours, significant figure	Third colour, multiplier	10 pF or under	over 10 pF
						%
Black . .	0	1	0	1	2 pF	20
Brown . 412	−3	10	1	10		1
Red . 538	−8	100	2	100		2
Orange . 557	−1·5	1,000	3	1,000	0·25 pF	2·5
Yellow . 355	−2·2	10,000	4	10,000		
Green . 221	−3·3		5		0·5 pF	5
Blue . 166	−4·7		6			
Violet . 796	−7·5		7			
Grey . 632	+3	0·01	8	0·01		
White . .	+1	0·1	9	0·1	1 pF	10

The colours shall be a close approximation to those shown above. The temperature coefficient and capacitance markings shall be clearly distinguishable from each other, preferably by showing them in that order and separated from each other by a space.

Example

Temperature coefficient .	1st colour, yellow 2nd colour, red .	= −220
Capacitance . . .	1st colour, brown 2nd colour, green 3rd colour, brown	= 150 pF
Tolerance . . .	4th colour, white	= ±10 per cent

AMERICAN COLOUR CODES

American colour codes for fixed capacitors may be of interest and are given below.

Unless otherwise indicated in the specific military electronic-part specification, the colours in military specifications are defined by

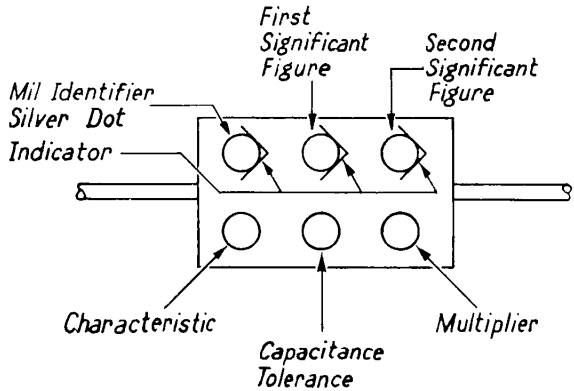


FIG. 2.16. U.S. STANDARD CODE FOR MOULDED-PAPER CAPACITORS (SPECIFICATION MIL-C 91)

standard MIL-STD-174, Colours for Coding Electronic Parts. Colours in accordance with EIA specifications are covered by EIA standard GEN-102.

PAPER-DIELECTRIC CAPACITORS

Moulded-paper capacitors, in accordance with specification MIL-C-91, may be marked with a colour code as shown in Fig. 2.16 and Table 2.6 if insufficient space prohibits full markings. The colours shall be in the form of six dots arranged in two rows of three dots each with an indicator to show the order in which they are to be read.

MICA-DIELECTRIC CAPACITORS

Mica-dielectric capacitors (moulded axial-lead types), under military specification MIL-C-5, must be marked with type designation.

TABLE 2.7. COLOUR CODE FOR MICA CAPACITORS IN ACCORDANCE WITH SPECIFICATION MIL-C-5B

Colour	Characteristic†	Capacitance		Capacitance tolerance (% ±)	D.C. working voltage	Operating temperature range	Vibration grade
		First and second significant figures	Multiplier				
Black	—	0	1	—	—	(*M*) −55 to +70°C	(1) 10–55 c/s
Brown	B	1	10	—	—	—	—
Red	C	2	100	2 (*G*)	—	(*N*) - 55 to +85°C	—
Orange	D	3	1,000	—	300	—	—
Yellow	E	4	—	—	—	(*O*) −55 to +125°C	(3) 10–2,000 c/s
Green	F	5	—	5 (*J*)	500	—	—
Blue	—	6	—	—	—	(*P*) −55 to +150°C	—
Purple (violet)	—	7					
Gray		8					
White		9	—	—		—	—
Gold		—	0·1	—	—	—	—
Silver	—	—	—	10 (*K*)	—	—	—

* The multiplier is the factor by which the two significant figures are multiplied to yield the nominal capacitance.
† The characteristic is a single letter which indicates the relative stability of the capacitor with temperature change.

capacitance, working voltage, and manufacturer's name or symbol, or with colour code to denote these characteristics.

The commercial types in accordance with EIA specification RS-153 follow the same colour code. (First six dots only.)

The military colour code for mica capacitors consists of nine dots

TABLE 2.6. U.S. COLOUR CODE FOR MOULDED-PAPER CAPACITORS (SPECIFICATION MIL-C-91)

Colour*	Capacitance		Capacitance tolerance, %(±)	Characteristic
	First and second significant figures	Multiplier†		
Black	0	1	20 (*M*)	*A*
Brown	1	10	—	*E*
Red	2	100	—	—
Orange	3	1,000	30 (*N*)	—
Yellow	4	10,000	—	—
Green	5	—	—	—
Blue	6	—	—	—
Purple (violet)	7	—	—	—
Gray	8	—	—	—
White	9	—	—	—
Silver	—	—	10 (*K*)	—

* The MIL identifier shall be a silver dot.
† The multiplier is the factor by which the first two significant figures are multiplied to yield the nominal capacitance.

arranged in three rows of three with an arrow indicator to show in which direction the dots are to be read, as shown in Fig. 2.17. The colour code for the dots is given in Table 2.7.

All button mica-dielectric capacitors, in accordance with specification MIL-C-10950, are marked by colour coding. The colours are shown in the form of six dots arranged clockwise, as shown in Fig. 2.18. For colours used in standard code see Table 2.7. These capacitors are available only in characteristics *C* and *D*.

GLASS CAPACITORS

Glass-dielectric capacitors for military use in accordance with requirements of specification MIL-C-11272 shall be marked either with the type designation or colour code. The colour code is the same as shown for moulded-mica capacitors (first six dots only). These capacitors are available only in characteristic *C*.

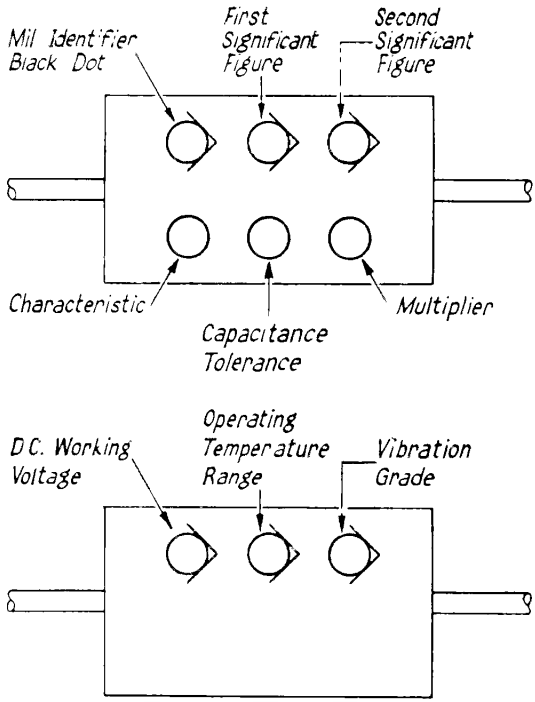


FIG. 2.17. U.S. STANDARD CODE FOR MOULDED-MICA CAPACITORS (SPECIFICATION MIL-C-5)

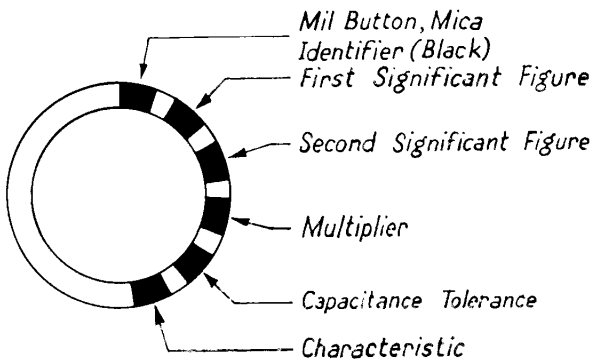


FIG. 2.18. U.S. STANDARD CODE FOR BUTTON-MICA CAPACITORS (SPECIFICATION MIL-C-10950)

Ceramic-dielectric Capacitors

Temperature-compensating-type ceramic-dielectric capacitors in accordance with specification MIL-C-20 can be marked either with type designation, capacitance tolerance, and temperature coefficient, or with a colour code consisting of five bands, as shown in Fig. 2.19.

Table 2.8. Colour Code for Ceramic Capacitors in Accordance with Specification MIL-C-20

Colour	Characteristic*	Nominal capacitance, pF: First and second significant figures	Nominal capacitance, pF: Multiplier†	Capacitance tolerance: For nominal capacitances greater than 10 pF (%)	Capacitance tolerance: For nominal capacitances of 10 pF or smaller, (pF)
Black	*C*—(0)	0	1		±2·0 (*G*)
Brown	*H*—(−30)	1	10	±1 (*F*)	
Red	*L*—(−80)	2	100	±2 (*G*)	±0·25 (*C*)
Orange	*P*—(−150)	3	1,000		
Yellow	*R*—(−220)	4			
Green	*S*—(−330)	5		±5 (*J*)	±0·5 (*D*)
Blue	*T*—(−470)	6			
Purple (violet)	*U*—(−750)	7			
Gray		8	0·01		
White		9	0·1	±10 (*K*)	±1·0 (*F*)
Gold	*A*—(+100)				

* The characteristic is a two-letter symbol identifying the nominal temperature coefficient and the envelope for the temperature-coefficient tolerance, respectively. However, the characteristic band or spot identifies only the nominal temperature coefficient.

† The multiplier is the factor by which the two significant figures are multiplied to yield the nominal capacitance.

The standard colour code is shown in Table 2.8. Commercial types under EIA specification RS-165 use the same colour code.

General-purpose ceramic capacitors (disc or tubular) meeting marking requirements of specification MIL-C-11015 may be marked with type designation, characteristics, capacitance and manufacturer's name or symbol, or with a colour code if required by shape or limited space, as shown by Fig. 2.20. The standard code is shown in Table 2.9. Capacitors are generally divided into classes according to their dielectric, e.g. paper, mica, ceramic, etc. It is useful to a designer to know the chief characteristics of these classes of capacitor, and the main characteristics are briefly outlined in the following tables and paragraphs.

TABLE 2.9. U.S. COLOUR CODE FOR CERAMIC CAPACITORS
(SPECIFICATION MIL-C-11015)

Colour	Temperature range and voltage-temperature limits*	Nominal Capacitance		Capacitance tolerance (%)
		Significant figure	Multiplier†	
Black	—	0	1	±20 (*M*)
Brown	*AW*	1	10	±10 (*K*)
Red	*AX*	2	100	
Orange	—	3	1,000	
Yellow	—	4	—	+80 (*X*) — 20
Green	*CZ*	5		
Blue	—	6		
Purple (violet)	—	7		
Gray	—	8		
White	—	9		

* The operating temperature range and the voltage-temperature limits are identified by two letters. The first letter indicates the operating temperature range, and the second, the voltage limits or allowable capacitance variation at specified temperatures, both with and without rated voltage applied.

† The multiplier is the factor by which the two significant figures are multiplied to yield the nominal capacitance.

TABLE 2.10. COMMON APPLICATIONS AND CHARACTERISTICS OF FIXED CAPACITORS

Type	Common applications	Commonly used capacitance values	Power factor (%)	Permittivity	Capacitance density
Paper	Blocking, buffer, bypass, coupling, filtering	0·001–1 μF	0·03–5	2–6	0·1–4 μF/in.³
Plastic film	Blocking, buffer, bypass, coupling, filtering	0·001–0·1 μF	0·02–5	2–4	0·09–3·6 μF/in.³
Mica	Blocking, buffer, bypass, coupling, filtering, tank	1 pF–0·01 μF	0·02–5	6·5–8·5	0·01–0·06 μF/in.³
Glass	Blocking, buffer, bypass, coupling, filtering, tank	1 pF–0·01 μF	0·04–10	8·4	Up to 4 μF/in.³
Vitreous enamel	Blocking, buffer, bypass, coupling, filtering, tank	1 pF–0·0068 μF	0·04–10	7	Up to 15 μF/in.³
Ceramic	Blocking, buffer, bypass, coupling, filtering, tank, temperature compensation	1 pF–0·01 μF	0·04–3	6–10⁴	0·1–3 μF/in.³
Aluminium-oxide electrolytic	Bypass, filtering	4–40 μF	15–35	7	1–13 μF/in.³
Tantalum oxide	Bypass, filtering	1–20 μF	10–25	20–27	1–20 μF/in.³
Vacuum, gas	High-power bypass, etc.	1–5,000 pF	0·02	1	3 pF/in.³
Air	Coupling, tuning, neutralizing	0·5–320 pF	0·02	1	0·6 pF/in.³

THE CHOICE OF A CAPACITOR—GENERAL CHARACTERISTICS

Table 2.10 first outlines the common applications of fixed capacitors, together with some comparison characteristics. The last column gives the approximate capacitance in one cubic inch of space.

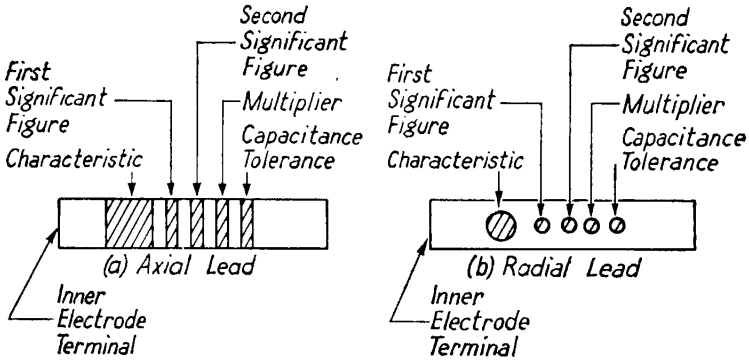


FIG. 2.19. U.S. STANDARD CODE FOR CERAMIC CAPACITORS (SPECIFICATION MIL-C-20)

A further classification was introduced by T. R. Scott at an I.E.E. Conference on Components and Materials in 1961 in which constructions and main features were summarized as in Table 2.11.

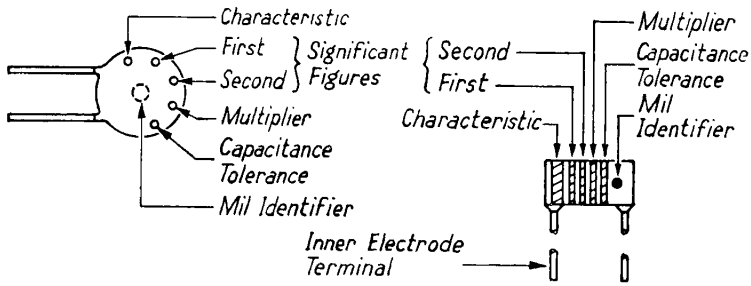


FIG. 2.20. U.S. STANDARD CODE FOR DISC OR TUBULAR CERAMIC CAPACITORS

Whilst these two tables give general guidance on capacitors, the author has prepared a more detailed summary of the actual types available in the United Kingdom. These are shown in Table 2.12.

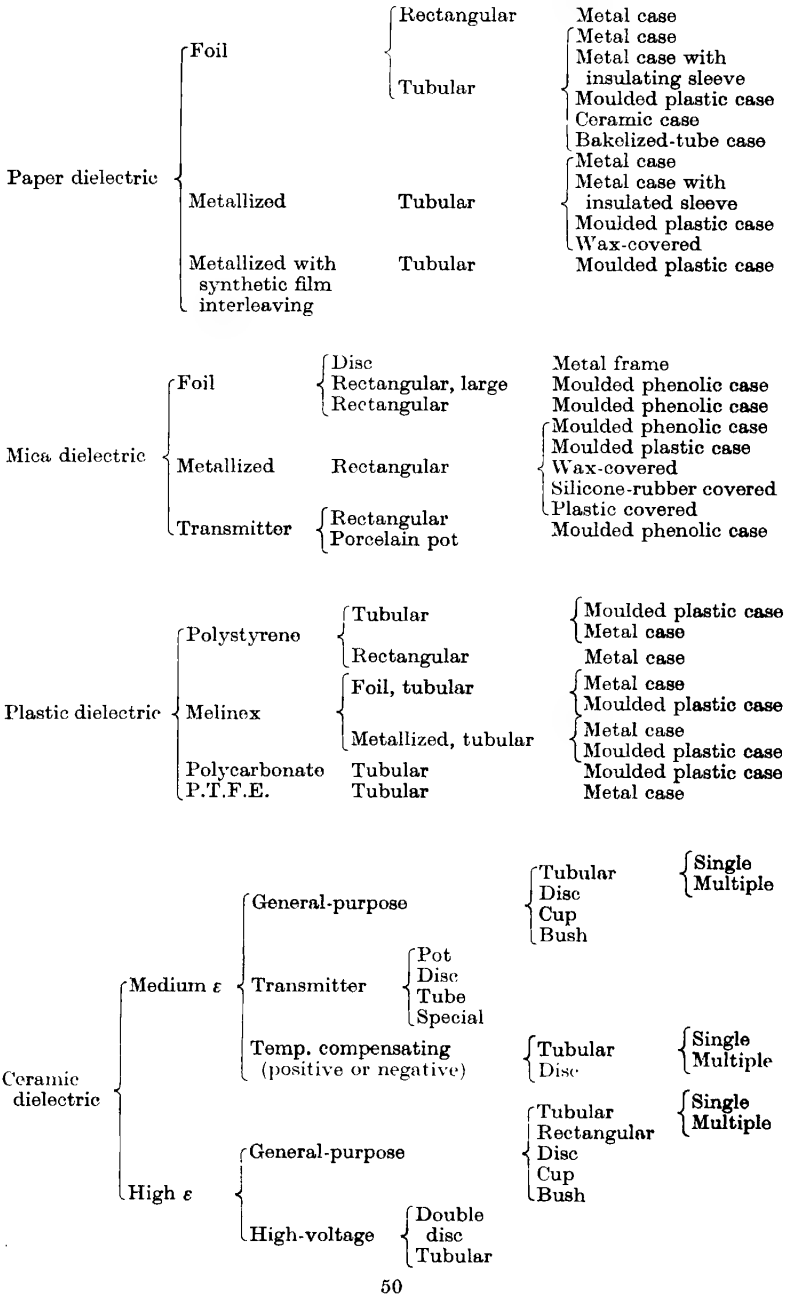
The electrical characteristics vary widely, and the following paragraphs attempt to summarize the main features of each class of capacitor.

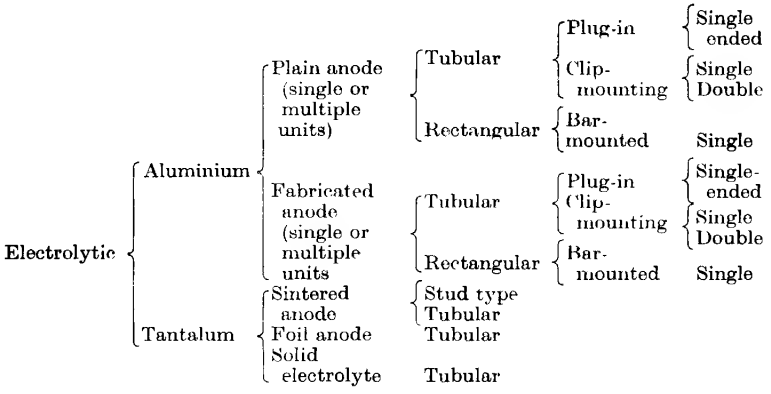
TABLE 2.11. CONSTRUCTION AND MAIN FEATURES OF FIXED CAPACITORS

Class	Name	Construction: Electrode	Construction: Dielectric	Features	Typical examples
1	Vacuum or gas	Metal sheet, rod or tube	Vacuum or gas	A close approximation to the "ideal" capacitor	Vacuum capacitor
2	Foil and film capacitors (including stacked and ribbon types)	Self-supporting metal foil	Self-supporting film, sheet or plate	A substantial improvement in space factor at nominal d.c. working voltages (e.g. 250) compared with Class 1. The improvement in space factor increases as the degree of departure from the "ideal," but a fair can be obtained to the "ideal" with an improved space factor using non-polar dielectrics in the form of films down to 6–9 μm in thickness. The minimum d.c. voltage for optimum space factor in this class is about 250	Impregnated paper Mica Polystyrene Polyethylene teraphthalate Polytetrafluoroethylene Polycarbonate
3	Metallized-dielectric capacitors	Metal deposited chemically, by condensation from a vapour or by sputtering and requiring support	Self-supporting in foil, tube, cup, or plate form	Metallized electrodes are used for two different purposes sub-classified as under.	Mica
	A. Contact Improvement			3A. To improve the intimacy of contact with the dielectric and so avoid the problems arising from a "mixed" dielectric. For non-resilient dielectrics or those not available in planar form, metallization is the only method of obtaining an adequate contact. A minor improvement in space factor generally occurs, since the supporting metallized electrode is generally thinner than its self-supporting counter-part.	Ceramic, low loss, relaxation polarized Wound Rod Monolithic Reduced
	B. Space factor improvement			3B. To further improve the space factor compared with that achieved in Class 2, by utilizing a thinner dielectric for the same normal working voltage. In Class 2 the presence of major inhomogenities (e.g. conducting particles) in the dielectric is avoided by using an excessively thick dielectric (generally in multi-layer form). In Class 3B the electrodes are fusible and the area of homogenity is isolated using this feature. The minimum d.c. voltage for optimum space factor is about 150.	Impregnated paper Polyethylene terephalate Cyanoethyl cellulose

Class	Name	Construction		Features	Typical Examples
		Electrode	Dielectric		
4	Deposited-dielectric capacitors A. Coated	One or both electrodes deposited chemically, by condensation from a vapour or by sputtering and requiring support	Deposited from a solution, by condensation from a vapour, by cataphoresis or by sputtering reactively or otherwise, on the electrode as a support	To obtain improved space factors at voltages lower than those achieved in Class 3 but without material change in the prime characteristics. The minimum d.c. voltage for optimum space factor for designs in current production is about 50, but reductions to 3 or so are envisaged. Two techniques are employed sub-classified as under. 4A. The deposition of a dielectric on either or both electrodes not derived from the electrode and applied by any coating process.	Coated foil Silicon monoxide Silicon dioxide Tantalum oxide Magnesium fluoride Zinc sulphide Cryolite (Na_3AlF_6) Glasses Lead titanate
	B. Surface formed		Formed by chemical or electrolytic action on one of the electrodes	4B. The deposition of a dielectric on one electrode derived from the material of that electrode, e.g. an anodic film.	Tantalum oxide Aluminium oxide Silicon dioxide
5	Electrolytic capacitors	One electrode is metallic and can be coated by an insulator by an anodizing process. The other electrode must provide ions when required, and generally an auxiliary electrode is necessary. As described the capacitor is "polar" or irreversible. If the electrode and counter-electrode can both be suitably anodized the capacitor becomes "non-polar or reversible	The layer formed by anodizing the electrode	To obtain space factors which are a further improvement on those in Class 3 but permitting or utilizing a degradation in the prime characteristics arising from the introduction of series resistance.	Aluminium Tantalum foil Tantalum slug Niobium Tantalum, dry Aluminium, dry
6	Semiconductor capacitors	One electrode is a *p*-type semiconductor and the other an *n*-type. Auxiliary electrodes may be required	The junction of the *p*- and *n*-type semiconductors	To obtain capacitance values that are very dependent on dielectric stress for use as a control device, modulator, demodulator and parametric amplifier.	Silicon

TABLE 2.12. CONSTRUCTION OF FIXED CAPACITORS





IMPREGNATED-PAPER CAPACITORS

These are general-purpose paper-dielectric capacitors, made by rolling paper as insulation between metal foils, and filling with an impregnant to increase the capacitance and working stress. They are relatively inexpensive, have a high capacitance-to-volume ratio and are capable of working at reasonably high voltages, but their power factor is comparatively high and the selection tolerances are fairly wide. The maximum permissible d.c. working voltage of any impregnated-paper capacitor is dependent on the ambient temperature, and the life of the capacitor is approximately inversely proportional to the fifth power of the operating voltage up to 85°C. Normal Service voltage de-rating figures for 85°C operation are 85 per cent of the 70°C working voltage, and for 100°C operation, 75 per cent of the 70°C working voltage. Irrespective of the d.c. working voltage, the maximum a.c. working voltage of a normal impregnated-paper capacitor with solid or semi-solid impregnant is about 300 V r.m.s. at 50 c/s for the tubular type and 600 V r.m.s. for the rectangular type containing two capacitor units in series. If higher a.c. working voltages are required, specially designed capacitors should be used.

The *RC* product of impregnated-paper capacitors is high at room temperature—of the order of 2,000 to 5,000 Ω-F (depending on the paper and impregnant) but falls rapidly as the ambient temperature is increased. Rectangular-cased types of 8 μF capacitance may fall to a few tens of megohms at a temperature of 100 C, whilst the tubular types of 0·1 μF capacitance (having a higher initial insulation resistance) may fall to a few hundred megohms at the same temperature. The fall in insulation resistance tends to be inversely proportional to the capacitance from one microfarad upwards, depending upon leakage over the case. The temperature coefficient of impregnated-paper capacitors

varies from + 100 to + 200 parts per million per degree centigrade (ppm/°C). The power factor is about 0·005 to 0·01 at 1 kc/s and tends to increase with increase of frequency. The capacitance stability under normal operating conditions is about 0·5 to 5 per cent. The inductance of the tubular types is approximately 0·015 μH per inch length of capacitor (including lead lengths). These characteristics apply mainly to the "radio type" paper capacitors. High-quality oil-filled capacitors can show considerable improvements. With the increasing use of transistors, with low operating voltages, care should be taken in the use of paper capacitors when either the d.c. or a.c. voltages are below 10 V, as some pressure contacts require appreciable current to maintain their low resistance. Special capacitors may be made, with increased area of contact, for these low voltages.

Metallized-paper Capacitors

These obviate voids between paper insulation and the metal, and were introduced in the late 1940's. In this type, one side of the paper is metallized before rolling. The main characteristics are small size and self-healing action under voltage stress. If the paper is punctured by excess voltage the metallizing quickly evaporates around the puncture and prevents a short circuit. The maximum voltage at which the self-healing action will occur without deterioration of the capacitor properties is termed the test voltage. It is about 1·5 times the working voltage and should never be applied for more than one minute at a time. The maximum voltage which may be applied instantaneously without destroying the capacitor is termed the spark voltage. It is approximately 1·75 times the working voltage and should never be applied for more than a few seconds, as continuous sparking will rapidly destroy the capacitor.

The RC product of metallized-paper capacitors is of the order of 100 Ω-F and is generally ten or twenty times less than for the ordinary foil-and-paper type, although some recent types (such as the W 97 made by A. H. Hunt, Ltd.) are comparable to foil types. The capacitor cannot, therefore, be used for coupling, but may be used for decoupling or smoothing, where the primary requirement is low impedance. Metallized-paper capacitors should not be used where frequent surges over the normal working voltages are likely to occur, otherwise deterioration in capacitance, power factor and insulation resistance will result. If two capacitors are used in parallel a resistor of 1,000 Ω is usually connected in series with each, to prevent any transient surges, which might occur if one capacitor failed, from affecting the other. The power factor of this type of capacitor is about 0·02 at 1,000 c/s and the capacitance stability about 5 to 10 per cent under service conditions.

Mica-dielectric Capacitors

The main characteristics of this type of capacitor are low power factor, high-voltage operation and excellent long-term stability at room temperature. The stability of the silvered-mica-plate type is about 1 per cent under normal conditions of use, and that of the stacked-mica-plate type, about 2 per cent. Precision mica capacitors, used as sub-standards, can be adjusted to better than 0·01 per cent for values over 1 μF. They are invariably sealed in cases to prevent moisture, etc., from affecting the stability. Capacitors of this type have remained constant in capacitance within $\pm$ 0·2 pF on a value of 10,000 pF over a test period of 10,000 hr at room temperature. The temperature coefficient is low, between $\pm$ 100 ppm/°C, but varies according to the source, treatment, etc., of the mica. The silvered-plate capacitor has a better temperature coefficient than the stacked-plate type. Both types, especially the stacked-plate capacitor, show slight non-cyclic capacitance shifts during temperature cycling, and in most of the types available at present, the temperature/capacitance curve is not entirely linear. There is also a wide spread of mean temperature coefficients between different specimens, even of the same batch. Good temperature coefficients are obtained on the wax-covered type with mica protecting plates, but resin-moulded types have better linearity in temperature coefficient over a temperature range of $-$ 40°C to $+$ 100°C and are normally used in Service equipments in preference to the wax-covered types.

The power factor of mica is approximately 0·0003 at 1 Mc/s, but can be as low as 0·00005 when specially selected and very dry. The permittivity is about 7. The current-carrying capacity of the silvered plate imposes a limit to radio-frequency and pulse loading, and the silvered-plate capacitor is therefore less suitable for heavy-current work than the stacked-plate type. The latter, however, is less stable and cannot be made to such a close selection tolerance as the silvered-plate capacitor.

Ceramic-dielectric Capacitors

Ceramic-dielectric capacitors ("ceramic capacitors") are made in three main classes—low-permittivity low-loss types, medium-permittivity temperature-compensating types and high-permittivity types.

The low-permittivity low-loss types are generally made of steatite or similar material. Steatite has a permittivity of approximately 8·0, and similar materials may give permittivities between 6·0 and 15·0. Their performance at high frequencies, from about 50 kc/s upwards, is excellent. The power factor is reasonably low (0·001), approaching that of mica. The temperature coefficient is between $+$ 80 and $+$ 120 ppm/°C and the capacitors are normally very cyclic in behaviour. The temperature

coefficients vary less between different batches than for capacitors of any other dielectric, except glass and vacuum. The capacitance stability in normal use is about 1 per cent, excluding temperature variations. They operate at comparatively high voltages, 500 V or so (depending on size), over a temperature range from about + 150°C down to extremely low temperatures.

The second class, of medium permittivity (ε about 90), are used mainly as temperature-compensating capacitors in tuned circuits and have negative temperature coefficients of the order of — 600 to — 800 ppm/°C. They are all based on titania or its derivatives. The power factor is again low and may be less than 0·0003 at radio frequencies. Other temperature coefficients can be obtained by using different mixtures.

The high-permittivity ceramic capacitors provide a very high capacitance in a compact unit. The capacitance and the power factor, however, change widely with temperature, the changes being neither linear nor very cyclic for either property. Capacitors using the $\varepsilon = 1{,}200$ material, for instance, have a high capacitance peak (Curie point) at about 110°C, which is two or three times the value at room temperature, with another much smaller one at about — 10°C. The power factor is a minimum around 20°C to 40°C and is, in general, around 2 per cent. High-permittivity materials with other permittivities have peaks at other temperatures. In general, the higher the permittivity, the more temperature-sensitive is the capacitor. In addition to changes with temperature, the capacitance is also reduced under d.c. voltage stress, especially at the peak points; at room temperature a reduction in capacitance of 10 to 20 per cent will occur, but up to 50 per cent can be expected at the Curie points. The d.c. working voltage is rather lower than for the low-permittivity ceramic type. The capacitors are subject to hysteresis and accordingly are only suitable for working with very small a.c. voltages. They are used mainly as r.f. by-pass capacitors, but can also be used for interstage coupling, provided that the capacitance is large enough under all conditions of operation. The properties of high-permittivity capacitors, therefore, vary so much with temperature, voltage stress, etc., that no general electrical characteristics can be given.

Glass-dielectric Capacitors

These capacitors are formed of very thin glass sheets (approximately 0·0005 in. thick) which are extruded as foil. The sheets are interleaved with aluminium foil and fused together to form a solid block. Their most important characteristics are the high working voltages obtainable and their small size compared with encased mica capacitors. Voltage ratings have been quoted in the U.S.A. as follows.

Capacitance (pF)	D.C. working voltage (V)
50	5,000
100	7,500
360	10,800
470	15,000

Glass-dielectric capacitors ("glass capacitors") have a positive temperature coefficient of about 150 ppm/°C, and their capacitance stability and Q-factors are remarkably constant. The processes involved in the manufacture of glass can be accurately controlled, ensuring a product of constant quality, whereas mica, which is a natural product, may vary in quality. As the case of a glass capacitor is made of the same material as the dielectric, the value of the Q-factor is maintained at low capacitances, whilst the low-inductance direct connections to the plates maintain the Q-factor at high capacitances.

These capacitors are capable of continuous operation at high temperatures and can be operated up to 200°C. They are also being developed for use as high-voltage capacitors in transmitters. Both types are being experimentally produced in this country.

Glaze- or Vitreous-enamel-dielectric Capacitors

Glaze- or vitreous-enamel-dielectric capacitors ("glaze or vitreous-enamel capacitors") are formed by spraying a vitreous lacquer on metal plates which are stacked and fired at a temperature high enough to "vitrify" the glaze. Capacitors made in this way have excellent r.f. characteristics, exceedingly low loss and can be operated at high temperatures, 150 to 200°C. As they are "vitrified" into a monolithic block they are capable of withstanding high humidity conditions and can also operate over a wide temperature range. The total change of capacitance over a temperature range of − 55°C to + 200°C is of the order of 5 per cent. The temperature coefficient is about + 120 ppm/°C and the cyclic or retrace characteristics are excellent. As in the glass capacitor the encasing material is the same as the dielectric material, and therefore all corona at high voltages is within the dielectric. They are extremely robust and the electrical characteristics cannot normally change unless the capacitor is physically broken. Capacitors of this type have been made in the U.S.A. and are now being made in this country.

Plastic-dielectric Capacitors

Plastic-dielectric capacitors (in which the dielectric consists of a thin film of suitable plastic material) available at the present time are

mainly of the polystyrene-film type. The chief characteristic of this type of capacitor is its very high insulation resistance at room temperature. With increasing temperature, the insulation resistance of the polystyrene capacitor remains always much higher than that of paper, the rate of decrease being much the same as for paper, although the polystyrene-film type is restricted in its upper temperature limit. This type of capacitor is not generally suitable for use above about 60°C, although some low-capacitance types are satisfactory up to 85°C. The power factor is low—about 0·0002, comparable with that of mica—and is independent of frequency. It also has a low dielectric absorption, which enables it to be used in long-time-constant circuits. The temperature coefficient is negative and ranges up to about 200 ppm/°C. The capacitance stability should be of the order of 0·5 per cent and the permittivity is 2·5.

Other plastic materials used as dielectrics include Melinex (Terylene* or polyethylene terephthalate), polythene, polytetrafluoroethylene (P.T.F.E.), etc. Capacitors using these materials are described in detail in Chapter 7; Some of these are still in the experimental or early preproduction stage.

Melinex is a most promising material and may in time replace paper to a considerable extent. It is, however, temperature- and frequency-sensitive. Its operating temperature is much higher than that of paper —up to 130°C. In single foils, Melinex may be impregnated with polystyrene, mineral oil, etc., to fill pinholes, or two films may be used (as in the case of paper-dielectric capacitors). The films have good mechanical strength and can be readily vacuum-metallized. Such films are, however, sensitive to moisture and the capacitors need to be hermetically sealed.

P.T.F.E. has the advantage of operating at still higher temperatures —as high as 250°C—but it is difficult to produce in thin films. Irradiated polythene has advantages, being a dielectric with similar characteristics to polythene and a higher operating temperature—about 110°C—but many difficulties have to be overcome before it can be used generally.

Electrolytic Capacitors

The most notable characteristic of these capacitors is the large capacitance obtainable in a given volume, especially if the working voltage is low. Electrolytic capacitors are used for smoothing and by-passing low frequencies, but they can also be used for high-energy-pulse storage applications, such as photoflash and pulsed circuits. The electrical properties change widely under different conditions of use and some indication of these is given below.

* Melinex and Terylene are products of Imperial Chemical Industries, Ltd.

Capacitance. There is a slight increase (about 10 per cent) when the temperature is raised from 20°C to 70°C; a gradual decrease as the temperature is reduced to − 30°C, and a very rapid decrease at lower temperatures. The capacitance also decreases slightly as the applied frequency is increased from 50 c/s, giving a 10 per cent reduction at 10,000 c/s.

Power Factor. At 50 c/s and room temperature, the power factor is from 0·02 to 0·05. There is a slight increase at + 70°C and a large increase at − 30°C. A large increase also takes place as the frequency is increased and the power factor becomes about 0·5 at 10,000 c/s.

Leakage Current. This is normally considered instead of insulation resistance, which is very low in this type of capacitor. The leakage current varies directly with temperature, having quite a low value at − 30°C, but at + 70°C it is about ten times the value at room temperature. In addition, the leakage current increases with the applied load, being very high when the load voltage is first applied, but it falls rapidly and after about a minute tends to reach a stable value.

Impedance. There is a gradual increase in impedance as the temperature is reduced, until at − 30°C it is about twice the impedance at room temperature, whilst at still lower temperatures a much more rapid increase occurs. At temperatures above normal there are only slight variations. The impedance falls rapidly with increase of frequency and at 10,000 c/s is of the order of 2Ω for a 16-μF capacitor.

The normal type of electrolytic capacitor is made using plain foils of aluminium, but considerably increased capacitance can be obtained by using etched foils or sprayed gauze foils to increase the surface area. Electrolytic capacitors need to be re-formed periodically if they are stored for a considerable time. Re-forming is carried out by applying the working voltage through a resistor of approximately 1,000 Ω for one hour.

Tantalum-pellet electrolytic capacitors do not need re-forming and have an expected shelf life of more than ten years. They have the advantage of even greater capacitance in a small volume and the leakage current is extremely small—of the order of a few microamperes—enabling them to be used in circuits such as multivibrators. They have lower voltage ratings, however, and some types are expensive, but they are capable of operating over a temperature range from − 55°C to + 125°C with negligible change in capacitance. Tantalum-foil electrolytic capacitors are also extremely small in size and have a low leakage current. They can operate at higher voltages than the tantalum-pellet types, but cannot operate over as wide a temperature range. The power factor varies considerably with temperature and also with voltage rating. They should find wide use in the near future as transistor-circuit components.

TABLE 2.13. SUMMARY OF THE ELECTRICAL CHARACTERISTICS OF FIXED CAPACITORS

Capacitor Type	Capacitor Stability (After climatic tests) (%)	Normal Manufacturing Tolerance on Capacitance (%)	Best Manufacturing Accuracy (%)	Permittivity (ε)	Power Factor (at 1 kc/s)	Temperature Coefficient (ppm/°C)	Maximum Capacitor Temperature for Long Life (°C)
Impregnated-paper (rect. metal-cased and tubular capacitors)	5	± 20	5	approx. 5	0·005 to 0·01	+ 100 to 200	100
Metallized-paper tubular capacitors	5	± 25	5	5	0·005 to 0·01	+ 150 to 200	Normal 85 Special 125
Moulded stacked-mica capacitors	2	± 20 or ± 10	5	4 to 7	0·001 to 0·005	± 200	Up to 120 Depends on casing
Moulded metallized-mica capacitors	1	± 10	± 2	4 to 7	0·001 to 0·005	± 60	Up to 120 Depends on casing
Glass-dielectric capacitors	1	± 10	(± 1 down to 10 pF)	approx. 8	0·001	+ 150	200
Glaze-dielectric capacitors	1	± 10	1	5 to 10	0·001	+ 120	150
Ceramic-tubular, normal-ε capacitors	1	± 10	± 1	6 to 15 80 to 90	0·001	+ 100 − 30 − 750 (according to mix)	150
Ceramic tubular, high-ε capacitors	20	± 20	5 (low values) 1 (high values)	1,500 and 3,000 (may be higher)	0·01 to 0·02 (Varies with temperature, etc.)	− 1,500, varies. Non-linear	100
Polystyrene-film, tubular and rectangular, capacitors	> 1	± 20	5	2·3	0·0005	− 150	60–70
Polyethylene terephthalate (Melinex) capacitors	5	± 20	5	2 to 5, depending on frequency	0·01 at 1 kc/s, varies with temperature and frequency	Varies with temperature	130
Electrolytic, (normal) capacitors	10	− 20 to + 100	10	—	0·02 to 0·05	+ 1,000 to 2,000 approx.	70–85
Electrolytic, (tantalum-pellet) capacitors	5	± 20	10	—	0·05	+ 100 to 200	125
Electrolytic, tantalum-foil capacitors	10	± 10	5	—	0·05	+ 500	85
Precision-type air-dielectric capacitors	± 0·01	—	0·01	1	0·00001	+ 10	20

Air-dielectric Capacitors

Air-dielectric capacitors are used mainly as laboratory standards of capacitance for measurement purposes. With precision construction and use of suitable materials, they can have a permanence of value of 0·01 per cent over a number of years for large capacitance values.

Vacuum and Gas-filled Capacitors

Vacuum capacitors are used mainly as high-voltage capacitors in airborne radio transmitting equipment and as blocking and decoupling capacitors in large industrial and transmitter equipments. They are made in values up to 500 pF for voltages up to 12,000 V peak. Gas-filled types are used for very high voltages—of the order of 250,000 V. Clean dry nitrogen may be used at pressures up to 150 lb/in.^{2} They are specifically designed for each requirement.

General Summary of Electrical Characteristics

A brief summary of the electrical characteristics of the commonly used types of capacitor is given in Table 2.13.

CHAPTER 3

THE MEASUREMENT OF CAPACITANCE

THE precision measurement of capacitance over a wide frequency range is a complex subject to which a great many workers have devoted much attention over many years. This work is fully described in the literature and a number of references to more detailed information are given in the bibliography. Only a brief description will be given here, therefore, of the common methods of measurement of capacitance.

The impedance of any capacitor can be measured as though it consisted of a pure capacitance C_s in series with a pure resistance R_s, or as a pure capacitance C_p in parallel with a pure resistance R_p. Usually the series measurements are made at low frequencies and the parallel measurements at high frequencies. The accuracy of the measurements depends (particularly at the higher frequencies) on the type of equipment used, the elimination of discontinuities of lead lengths between the unknown capacitor and the measuring equipment, stray coupling to the unknown capacitor, and the sensitivity of the detector. Measurements of capacitance may be generally classified into those carried out at low frequencies and those carried out at high frequencies.

LOW-FREQUENCY MEASUREMENTS

Since stray series impedances are small at audio frequencies, measuring equipment can be made extremely accurate by screening and by careful arrangement of components and with good evaluation of correcting terms. Great care may be required with these measurements. Precision measuring equipment usually consists of a bridge network which can give an accuracy of measurement of one part in a million for capacitance and 0·000005 for power factor (under the most favourable conditions). Many high-precision bridges use mutual-inductance ratio arms. Typical bridges are described briefly in the following paragraphs.

THE CAREY-FOSTER BRIDGE

This bridge gives series components C_s and R_s, and a simple circuit diagram is shown in Fig. 3.1. In this arrangement M is a standard mutual inductometer, Q is a fixed standard resistor and R is the resistance of the self-inductance L.

Let R_s = resistance of unknown capacitor C_s.

Then $C_s = M/QR$ at balance

and the capacitor resistance $R_s = Q(L/M) - 1$

In practice the capacitance of the leads to the unknown capacitor is usually measured and subtracted from the value obtained with the unknown capacitor in circuit. The range of capacitance measurement

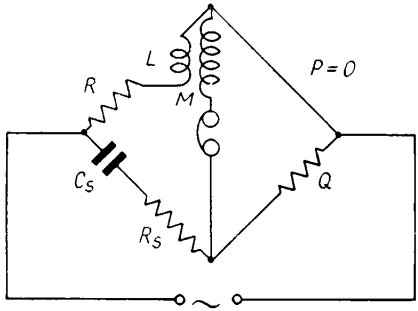


FIG. 3.1. CAREY-FOSTER BRIDGE CIRCUIT

of this bridge is up to about 10 μF, and an accuracy of better than one part in ten thousand can easily be obtained.

THE SCHERING BRIDGE

This bridge also gives series components, C_s and R_s, and a simple diagram of the circuit is given in Fig. 3.2. In this circuit C_2 is a stan-

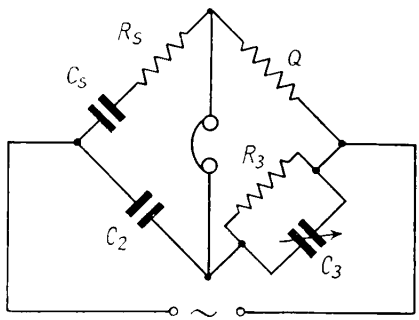


FIG. 3.2. SCHERING BRIDGE CIRCUIT

dard fixed capacitor, C_s is an unknown capacitor to be measured and R_s is the unknown series resistance of the capacitor C_s.

Then $C_s = R_3C_2/Q$ and $R_s = QC_3/C_2$ at balance

and $$\tan \delta = \omega R_3C_3 = \omega C_sR_s$$

where δ is the loss angle and $\omega = 2\pi \times$ frequency of supply.

This bridge is of the highest precision and has wide applications. Modified forms are used for most measurements of capacitors at audio frequencies, including measurements at voltages up to 100 kV.

General Types of Bridges

Bridges are also made in designs similar to those of the high-precision bridges mentioned above, but using lower-grade components and construction. Accuracies are of the order of 0·1 to 1·0 per cent. For example, the Cambridge Instrument Co. make a universal bridge which has an accuracy of 0·2 per cent for frequencies up to about 3 kc/s. There are many designs and variations of bridges of this type, with similar accuracies, which are in general use. A typical series-resistance bridge circuit is shown in Fig. 3.3.

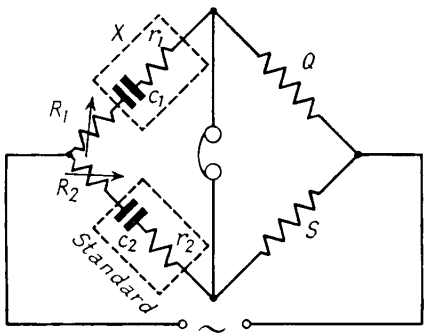


Fig. 3.3. Series-resistance Bridge Circuit

In this bridge arrangement Q and S are fixed known resistors, and we may write $P = R_1 + r_1$ and $R = R_2 + r_2$. C_2 is a standard capacitor and C_1 is the capacitor under measurement.

Then $$C_1 = C_2 S/Q$$

so that $$C_1/C_2 = S/Q = R/P \text{ at balance}$$

Then $$C_1(R_1 + r_1) = C_2(R_2 + r_2)$$

and $$\omega C_1 R_1 - \omega C_2 r_2 = \omega C_2 R_2 - \omega C_1 r_1$$

i.e. $$\tan \delta_1 - \tan \delta_2 = \omega C_2[R_2 - (S/Q)r_1]$$

This bridge gives the impedance in series terms but requires the power factor of the standard capacitor C_2 to be known in order to obtain the power factor of the unknown capacitor C_1. Typical measurement accuracies with this bridge are 0·2 per cent for capacitance and 1 to 2 per cent for resistance.

Substitution Methods

A most useful method at low frequencies is the substitution for the unknown capacitor of an accurately known capacitor. This does not give the resistive term but can give the capacitance to within 0·01 pF.

It has the advantage that the only accurate equipment needed is the standard variable capacitor, although a sensitive detector is also required. The method is limited to about 100 kc/s, depending on the frequency characteristics of the standard capacitor and the stability of the apparatus.

Small capacitances can be measured by noting the change in frequency of a tuned circuit (oscillator) when the unknown capacitor is

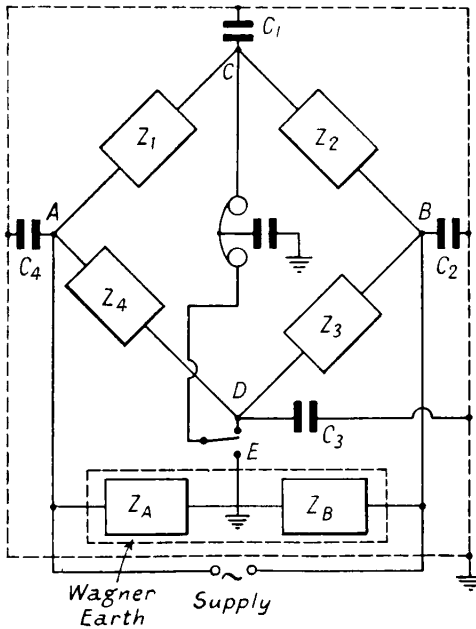


FIG. 3.4. CIRCUIT EMPLOYING WAGNER EARTH CONNECTION

placed in parallel with the circuit capacitance. If the frequency is above about 10 Mc/s, great care may have to be taken to avoid introducing errors due to stray capacitance and small inductances.

THE WAGNER EARTH

The Wagner earth connection is of great value in accurate bridge measurements since it can improve the sensitivity of a bridge by minimizing earth capacitance effects such as capacitance to the bridge case, etc.

A circuit employing a Wagner earth connection is given in Fig. 3.4. Capacitors C_2 and C_4, in series, shunt the supply and do not affect the bridge itself.

At balance, points C and D of the bridge are at the same potential,

but, because of C_1 and C_3, are not at earth potential. Since the detector itself is often coupled by stray capacitances to earth, a current may flow through the detector when the bridge is balanced.

The procedure is first to balance the bridge as well as possible, switch the detector to the mid-point of Z_A and Z_B and balance with these two impedances. Since this mid-point is earthed, point C will also be at earth potential and D is brought to earth potential by final balancing.

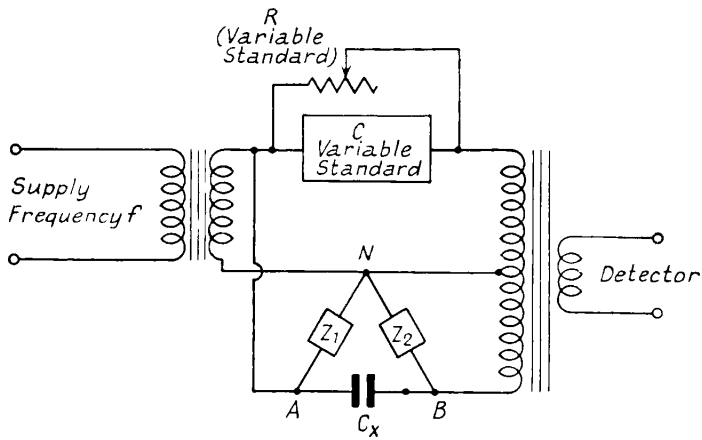


FIG. 3.5. TRANSFORMER BRIDGE

HIGH-FREQUENCY MEASUREMENTS

TRANSFORMER BRIDGES

Transformer bridges, which are mainly a post-war development, are now in use covering the frequency range 15 kc/s to 250 Mc/s. Above 50 Mc/s the bridges are designed mainly for the measurement of cable impedances, but by suitable arrangement of the bridge terminals they can be used for measuring small capacitances. The higher-frequency bridges are capable of measuring poor power factors only where the effective parallel resistance is between 10 Ω and 10 kΩ. The accuracy of the capacitance measurements is 1 to 2 per cent, or 0·5 pF, and of the resistance measurement 1 to 2 per cent, or, measured as a conductance, 0·025 millimho. It is, therefore, not possible to obtain an accurate value except for a poor capacitor.

Transformer bridges have the advantages of covering a wide frequency range and ease of measurement, and can measure inductance in terms of negative capacitance. The results are always in parallel terms.

A typical circuit diagram is shown in Fig. 3.5. The unknown capacitance is usually connected across terminals A and B. With three-terminal components N is used but only the capacitance between A

and B is measured, since the impedance Z_1 is directly shunting the supply and Z_2 is shunting the detector. The detector usually consists of a communication-type receiver and the supply is a modulated oscillator. Performances of some typical bridges are given below.

Muirhead Transformer Bridge

$f = 15$ kc/s to 2 Mc/s
$C = 0$ to $\pm$ 20,000 pF
$R = 10\ \Omega$ to 10 MΩ
Accuracy = 2 per cent

Wayne-Kerr Type B801A

$f = 1$ to 100 Mc/s
$C = 0$ to $\pm$ 250 pF
$R = 10\ \Omega$ to 10 kΩ
Accuracy = 2 per cent

Wayne-Kerr Type B901

$f = 50$ to 250 Mc/s
$C = 0$ to $\pm$ 75 pF
$R = 10\ \Omega$ to 10 kΩ
Accuracy = 5 per cent

Q-METERS

General-purpose Q-meters can be used to measure capacitance to an accuracy of approximately 5 per cent up to about 50 Mc/s. They can be modified to use external variable standard capacitors and voltmeters so that measurements can be made to an accuracy of 2 per cent up to about 20 Mc/s. Above this frequency stray capacitances and inductances introduce large errors. The Q-meter is, however, an extraordinarily versatile instrument, for it is capable of making almost any impedance measurement over a range from about 50 kc/s to 200 Mc/s. Q-meters can measure almost any impedance at an accuracy depending on the quality of the equipment. (The operation of a Q-meter is described in the section on the measurement of power factor (p. 71).)

The Hartshorn and Ward Dielectric Test Set

This equipment is an extremely accurate high-frequency apparatus and consists of a very carefully designed Q-meter covering the frequency range 10 kc/s to 100 Mc/s. It is specifically designed for measuring

flat-disc dielectrics or liquid dielectrics, but suitable jigs and terminal arrangements permit other components to be measured. The principle of the equipment is shown in Fig. 3.6.

The oscillator is inductively coupled to the tuned circuit L, R and C_2.

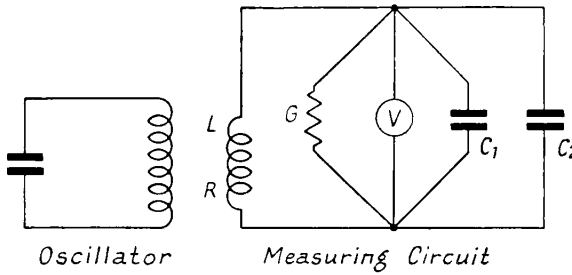


FIG. 3.6. BASIC DIAGRAM OF HARTSHORN AND WARD DIELECTRIC TEST SET

The unknown capacitance is C_1, and C_2 is an accurately calibrated variable capacitor. When C_1 is added to the tuned circuit C_2 is adjusted to bring the circuit back to resonance, and the change in C_2 is the value

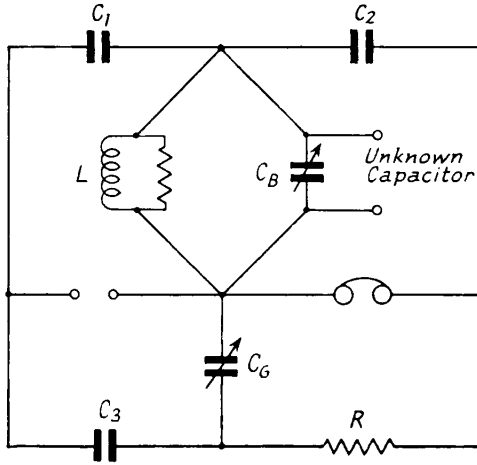


FIG. 3.7. TWIN-T BRIDGE

of the added capacitance. The conductance G of the tuned circuit, with and without C_1, is measured by the reactance variation method, from which the resistance of C_1 is determined. The accuracy of measurement is 1 per cent and the capacitance range is 0 to a few hundred pF. The power factor range is down to 0·0001.

Twin-T Bridges

Twin-T bridges are often used for measurements up to 50 or 100 Mc/s, with an accuracy of about 5 per cent. A simple diagram of a twin-T bridge is given in Fig. 3.7.

Two T-sections are connected in parallel. For null indication the sum of the transfer impedances of the two T-sections must be zero. The susceptance is measured by the change in the capacitor C_B (directly in pF). The conductance is measured by the change in the capacitor C_G, calibrated in microhms. R is a straight wire resistor, whose residual inductance at radio frequencies is compensated by a trimmer capacitor which is adjusted to give essentially zero effective reactance over the range of the bridge.

Twin-T bridges are now being designed for accurate measurements up to 150 or 200 Mc/s. By paying detailed attention to symmetry it is possible to extend the range, and a simple Wheatstone bridge has been designed in Germany which is reported to cover the frequency range 0·1 to 1,000 Mc/s (*see* Bibliography, p. 223).

Measurement of Capacitance of Electrolytic Capacitors

Special arrangements are necessary when measuring the capacitance of electrolytic capacitors. This type could obviously be measured on a normal bridge to determine its capacitance and power factor, but this would give no information regarding the leakage current likely to be encountered when used in a circuit. Also it is possible, particularly with polarized capacitors, that the results obtained will change from these values when used with a superimposed direct voltage. Again there is the danger that unless the alternating voltage applied to the bridge is kept to a very low value there will be excessive heating by the test current, with a tendency to de-form the capacitor, and, in the limit, for the capacitor to break down during the half-cycle when it is subject to a reverse potential. In a typical test equipment a re-forming direct voltage, not exceeding the rated working potential, is applied. This has the additional advantage of stabilizing the properties of the capacitor and thereby making further tests easier to perform. The leakage current is then checked, and having been found within tolerance the capacitor is connected into a bridge circuit similar to that shown in Fig. 3.8.

The frequency of the a.c. signal applied should, where possible, be the same as the operating frequency. For a smoothing capacitor it will be twice the mains frequency.

Measurements above 200 Mc/s

Above about 200 Mc/s, Lecher-wire (i.e. standing-wave) measuring apparatus is used, and this can give reasonably accurate results, but,

in general, small capacitors are not often used at these frequencies since the stray capacitances in circuits can introduce large errors. At frequencies higher than 200 Mc/s interest is generally centred on measurement of dielectric properties of materials.

METHODS OF MEASUREMENT OF THE PROPERTIES OF DIELECTRIC MATERIALS

Methods of measurement of capacitance from low frequencies up to about 200 Mc/s have been described, and these can be used to assess the dielectric properties of materials up to these frequencies. Above these

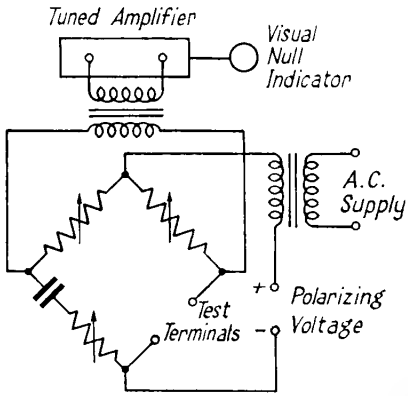


FIG. 3.8. BRIDGE FOR MEASURING CAPACITANCE OF ELECTROLYLITIC CAPACITORS

frequencies coaxial line, waveguide and resonant cavities are used, and the bibliography gives a number of references to work in this field. Very brief descriptions of the principles of these three methods are given below.

COAXIAL-LINE METHOD

From approximately 200 Mc/s to approximately 1,000 Mc/s coaxial lines are used, modulated c.w. being injected into a slotted coaxial line along which a probe (which is connected to a calibrated amplifier) can travel, as shown in Fig. 3.9. This line is terminated in a coaxial section in which the dielectric used is the material to be investigated, and the standing waves set up in the slotted line when this is terminated (usually by an open-circuit or a short-circuit, but sometimes by other convenient reactances) are measured on the amplifier.

The standing wave is specified by the ratio of the minimum to maximum voltages and by the position of the voltage maxima and minima in relation to the end of the line.

If the slotted line is terminated by a purely resistive load, the voltage maximum or minimum will occur at the end of the measuring section, the maximum occurring if the resistance is high compared to the characteristic impedance of the line and the minimum if the resistance is low.

The purely reactive load will lead to an apparently infinite standing-wave ratio, whilst if the load is perfectly matched to the line there is no reflection and consequently no standing wave is observed.

If the magnitude and phase of the standing-wave ratio have once been determined the nature of the terminating impedance can be

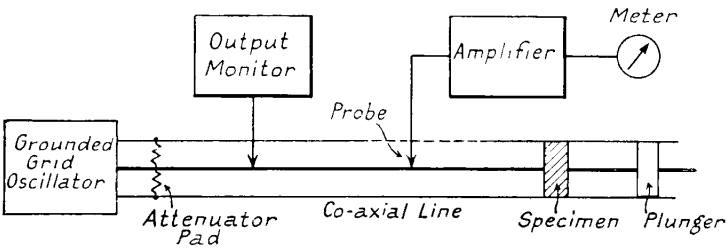


FIG. 3.9. COAXIAL-LINE MEASUREMENT OF DIELECTRIC PROPERTIES

expressed in terms of the characteristic impedance of a line by the following formula—

$$Z_i = Z_0(Z_i + jZ_0 \tan \theta)/(Z_0 + jZ_i \tan \theta)$$

where Z_i = input impedance,

Z_0 = characteristic impedance,

θ = electrical length of the test specimen (number of wavelengths).

According to whether the section under investigation is open- or short-circuited, or otherwise terminated, the impedance which it presents will differ. From the impedances found with two different terminations the propagation coefficient and impedance of the specimen can be found by means of the above formula. This is most conveniently done with the help of the Smith circle diagram, and for details of this calculation reference should be made, for instance, to the paper by Willis Jackson and Huxley, (*J. Instn Elect. Engrs.* **91**, Pt. III (1944) 105) on the solution of transmission-line problems. Other references are contained in the bibliography.

Waveguide Method

For frequencies of approximately 1,000 Mc/s to approximately 3,000 Mc/s the method of measurement may be as follows. The coaxial lines are replaced by waveguides, in which the fundamental processes are essentially as described above. The schematic diagram of the apparatus is shown in Fig. 3.10. A point to be remembered is that in the waveguide the wavelength is longer than its value in free space, due to wall-to-wall reflections, the difference depending upon the frequency and the guide dimensions. Under certain conditions the wave will not be propagated and is said to be cut-off. The filled section,

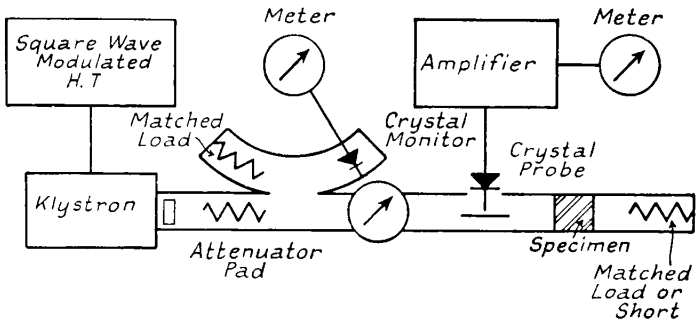


Fig. 3.10. Waveguide Method of Dielectric Measurement

however, will be worked under conditions far removed from cut-off and the propagation conditions will be almost exactly as in an infinitely extended medium. Bearing these corrections in mind, the essential calculations are similar to those described for coaxial-line methods.

Resonant Cavities

From approximately 3,000 Mc/s upwards resonant cavities can be used—essentially, oscillations are set up in a completely enclosed cavity of simple shape and their rate of decay is determined when a body of the material under investigation is introduced as an absorbing material. The most convenient form of cavity is cylindrical and a cylindrical sample is placed on the axis. Decay of the oscillations is determined from the bandwidth of the cavity used as the termination, in a manner precisely similar to that discussed with Q-meters at lower frequencies (p. 65).

In the case of very loss-free materials the specimen may be allowed to fill a good deal of the cavity, but the method can be applied to relatively lossy materials provided that the specimen is small. A diagram of the apparatus is given in Fig. 3.11.

THE MEASUREMENT OF POWER FACTOR

In the series bridges described in the previous paragraphs, the power factor is equal to $2\pi f rC$ where r is the series resistance. This is calculated directly from the readings of C and r on the bridges.

A parallel bridge differs from a series bridge in that the resistance

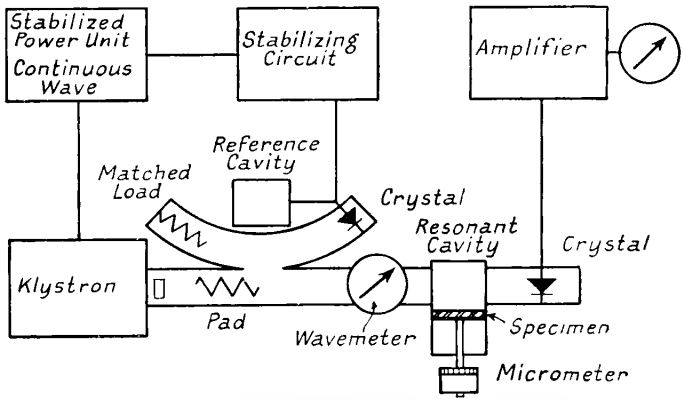


FIG. 3.11. RESONANT-CAVITY METHOD OF DIELECTRIC MEASUREMENT

shunts the capacitance instead of being in series with it. In this case the power factor is equal to $1/2\pi fRC$ where R is the parallel resistance.

A Q-meter can also be used. In this method the circuit is first tuned

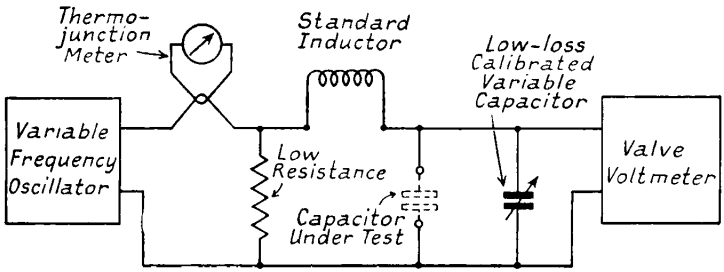


FIG. 3.12. METHOD OF DIELECTRIC MEASUREMENT WITH Q-METER

to resonance without the unknown capacitor in circuit and then retuned with the capacitor in parallel with the tuning capacitor, as shown in **Fig. 3.12.**

The resonance curve gives a measure of the capacitance, and also the loss of the capacitor and the power factor can be calculated from the

height and sharpness of this curve. The change in capacitance from the resonance point is taken at 0·707 of the peak voltage (Fig. 3.13).

If C = capacitance and ΔC = the change in capacitance (or half the width AB) then

$$Q = C/\Delta C$$

and

$$\text{power factor} = 1/Q = \Delta C/C$$

If the capacitor has very low losses a correction is necessary to allow for the losses in the measuring circuit, and the width of the bandpass curve without the unknown capacitor is subtracted from the width of the curve with the capacitor in circuit.

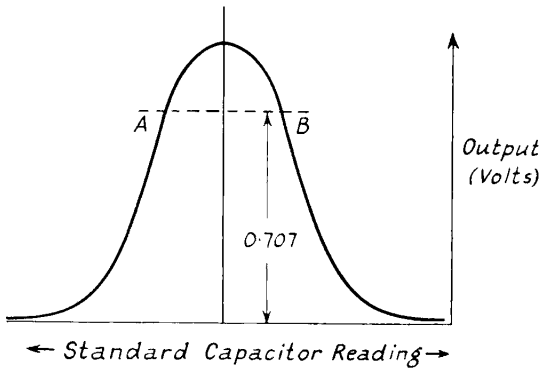


FIG. 3.13. RESONANCE CURVE

THE MEASUREMENT OF TEMPERATURE COEFFICIENT OF CAPACITANCE

The temperature coefficient of capacitance, α, of a capacitor is defined by the formula

$$\alpha = \Delta C/C\Delta t$$

If ΔC and C are expressed in the same units of capacitance and Δt is in degrees centigrade, this may be expressed as

$\alpha = \Delta C \times 10^6/C\Delta t$ parts per million per degree Centigrade (ppm/°C)

Increases of Δt and ΔC are taken as positive.

The equation implies linearity over the range of Δt, and thus a statement of the value of α should strictly be accompanied by a statement of the value of Δt over which it is calculated. All measurements are usually made at a frequency of 1 Mc/s.

Temperature-coefficient measurements are usually required on mica-, ceramic- and air-dielectric capacitors. Typical ranges of values covered by Service types of capacitor are shown in Table 3.1.

The closest temperature-coefficient tolerance at present is ± 20 ppm/°C and therefore any measuring apparatus must have an accuracy

TABLE 3.1

Type of capacitor	Range of temperature coefficients (ppm/°C)
Mica (stacked)	− 200 to + 200
Mica (metallized)	− 60 to + 60
Ceramic, tubular (positive t.c.)	0 to + 120
Ceramic, tubular (negative t.c.)	− 100 to − 800
Air, vane tuning	− 50 to + 50
Air, vane trimmer	− 100 to + 100
Air, miniature	+ 30 to + 70
Air, miniature trimmer	+ 40 to + 100

greater than this. For values of α equal to, or in excess of, 100 an accuracy of 1 per cent is considered adequate with a temperature measurement accuracy of 0·1 per cent. Modern measuring equipment is capable of measuring α to within 1 per cent, or 1 part in 10^6 per degree centigrade, whichever is the greater, for values of capacitance between 100 pF and 500 pF, over a temperature range of − 40°C to + 70°C.

FIG. 3.14. CAPACITOR SUBSTITUTION METHOD OF TEMPERATURE-COEFFICIENT MEASUREMENT

It is possible to detect a value of ΔC of 0·001 pF, with C determined to $\frac{1}{3}$ per cent and temperature maintained to within 0·1 per cent.

In temperature-coefficient measuring equipment the thermal and electrical requirements are quite distinct. The requirement is to measure the capacitance change, ΔC, of a fixed capacitor when its temperature is changed by a known amount. Although bridge methods could be used, the general method is by using resonant-circuit methods.

The resonant circuit forms the oscillatory circuit of a valve as shown in Fig. 3.14. If C_1 is the capacitor under test then a small change in its value, ΔC_1, can be measured either in terms of the change in oscillator frequency or by altering the value of the parallel capacitor C_2 to keep the frequency constant. A general method is to substitute C_2 for C_1 by means of a switch and to adjust the value of C_2 until the oscillator

frequency equals that obtained with C_1 in circuit. Under these conditions $C_1 = C_2$. This measurement is repeated at different temperatures. A typical measuring equipment of this type is shown in Fig. 3.15.

The outputs of the two oscillators O_1 and O_2 are combined at A, the resultant signal is rectified and the frequency difference is available at B. Oscillator O_2 may be set to the frequency of measurement (usually 1 Mc/s) and oscillator O_1 adjusted to a slightly different frequency to produce a beat note at B. This beat note is in turn combined with the output of a stable 1,000 c/s oscillator via a demodulator, and a further beat note is produced which can be fed to a cathode-ray oscillograph. By this means a change of about 2 or 3 c/s can be detected in the

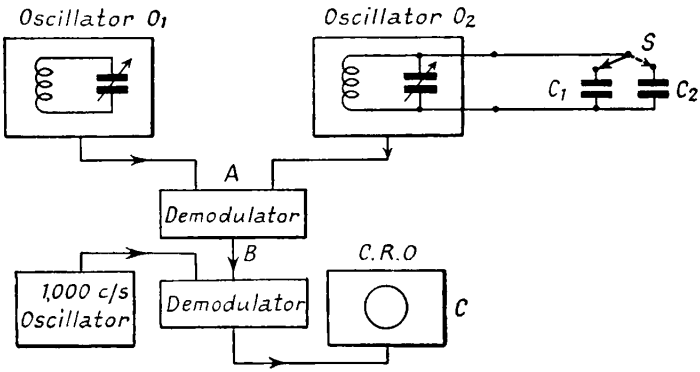


FIG. 3.15. APPARATUS FOR TEMPERATURE COEFFICIENT MEASUREMENT

original 1 Mc/s frequency, i.e. a change of frequency of O_2 of about 2 or 3 parts in 10^6.

The capacitor to be measured is placed in an oven and connected across the oscillatory circuit of O_2, and the frequency of O_1 is adjusted for zero beat at C. The capacitor being measured is then replaced by a standard capacitor having micrometer adjustment. The standard capacitor is adjusted until zero beat is again obtained. The oven is heated (to say 50°C) and the above process repeated. This will give a new reading on the standard capacitor. The change of reading of this capacitor equals the change of capacitance of the capacitor under test, and if the temperature rise of the capacitor is measured then the temperature coefficient can be calculated as described.

Measurements for Service capacitors are usually made three times. The capacitance and temperature are measured and recorded at room temperature. The temperature of the capacitor is then raised by 50°C, and after stabilizing, the capacitance and temperature are again recorded. The capacitor is then cooled to the original temperature and

measured again. This cycle is repeated three times and the temperature coefficient calculated for each of the six half-cycles as follows.

Temperature coefficient, α

$$= \frac{(C_2 - C_1) \times 10^6}{C_1(T_2 - T_1)} \text{ parts per million per degree Centigrade}$$

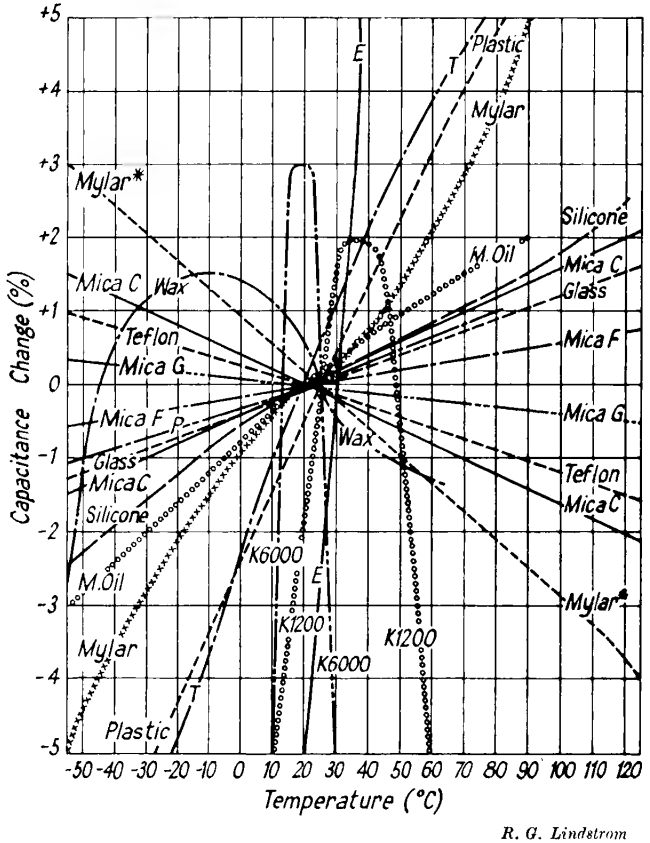


FIG. 3.16. CAPACITANCE/TEMPERATURE CHARACTERISTICS OF VARIOUS CAPACITORS

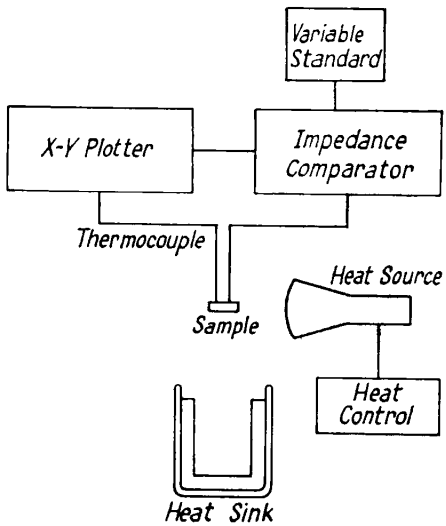
where C_1 = capacitance at the lower temperature, C_2 = capacitance at the higher temperature, T_1 = room temperature, and T_2 = higher temperature.

Typical graphs for various capacitors, by R. G. Lindstrom, show the wide variation in temperature coefficient (Fig. 3.16).

Dynamic Temperature Coefficient Measurement

A system of measuring the temperature coefficients of capacitors using radiant heating has been developed by the Vitramon Corporation, Bridgeport, Connecticut, U.S.A., and is described below.

The aim was to try to attain the ultimate in simplicity and elimination of all parts which introduce variables. The component is permitted to change in temperature continuously, for it is practical to measure the capacitance while the temperature is changing and thereby define its



Vitramon Corporation

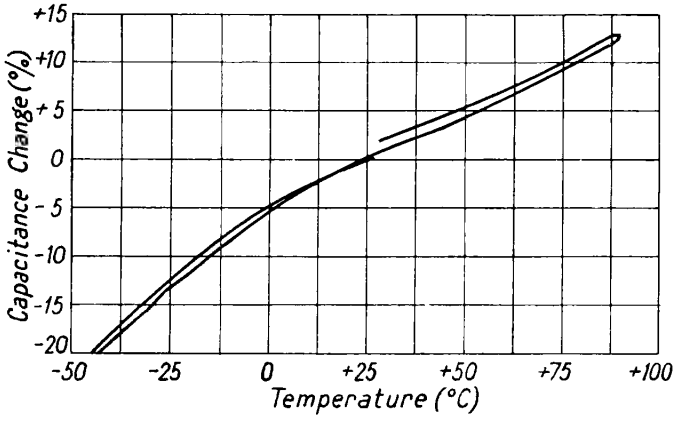
Fig. 3.17. Dynamic Method of Measuring Temperature Coefficient of Capacitance

temperature coefficient. This system is termed "dynamic temperature coefficient measurement" and can be accomplished with extremely simple equipment.

The method is illustrated in the block diagram, Fig. 3.17. Basically, the system is only a capacitor connected to a stable bridge. A minimum of leads and connecting devices is used. To attain this minimum condition, a method of causing the component to go through predicted changes in temperature without upsetting this simplicity is incorporated. A source or sink of heat is provided which can cause changes in temperature without creating spurious capacitance effects on the sample or its bridge connections. The test capacitor is enclosed in a shield (not shown), in order that convective heat transfer is restricted and

electrical disturbances are reduced. To measure the capacitor temperature, a thermocouple is attached to one terminal of the capacitor or is placed within a dummy component which is to the side of the sample. It can be established that, within practical limits, this thermocouple follows the temperature of the sample.

It is relatively simple to transfer heat into the component because the temperature difference between the radiant heat source and the sample can be large. Unfortunately, this same advantage cannot be realized in achieving a temperature near — 55°C. A maximum temperature

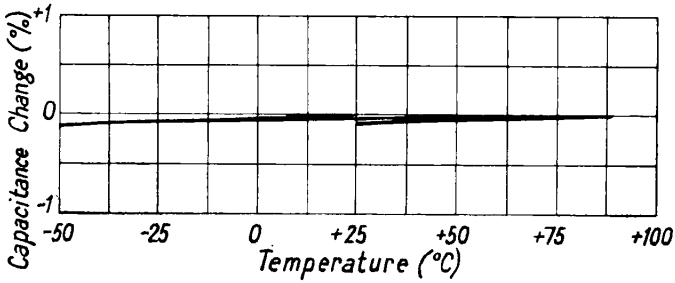


Vitramon Corporation

FIG. 3.18. CAPACITANCE/TEMPERATURE CHARACTERISTIC OF 0·001-μF PAPER CAPACITOR AT 100 KC/S

differential of only a few hundred degrees can be realized through the use of liquid gases; it is therefore difficult to produce negative temperatures through radiation exclusively and a more direct approach has been used as shown in Fig. 3.17. For a short time the sample is surrounded by a well which is immersed in liquid nitrogen, or dry ice in alcohol, thereby reducing the temperature of the component below — 100°C. After establishing the capacitor at this temperature, the well is retracted and the capacitor temperature is permitted to rise. By appropriately applying heat, the rate of rise of the test capacitor can be controlled so that it sweeps the entire temperature range — 55°C through 200°C at a smooth, known, predictable rate.

Analysis of the performance of this system indicates overall precision of measurement to be equivalent to $\pm$ 0·02 per cent change in capacitance. Thermal lags between the thermocouple temperature and the mean sample temperature have been studied through effects of thermal transients. If an alteration in the rate of temperature change affects the



Vitramon Corporation

FIG. 3.19. CAPACITANCE/TEMPERATURE CHARACTERISTIC OF MICA CAPACITOR

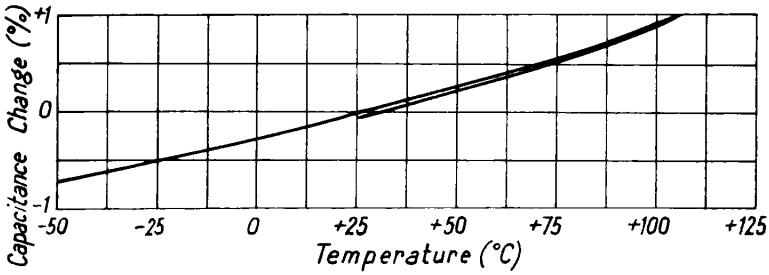


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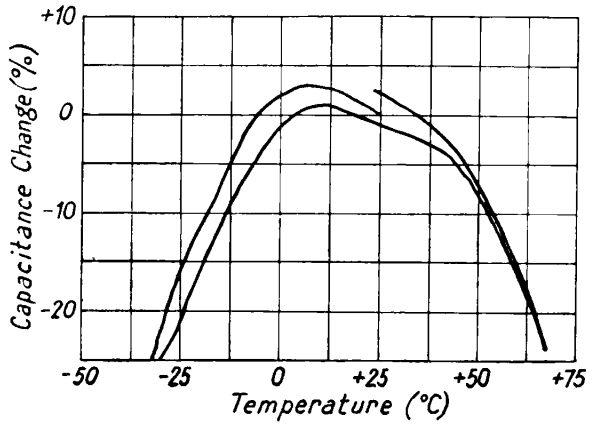
FIG. 3.20. CAPACITANCE/TEMPERATURE CHARACTERISTIC OF CERAMIC CAPACITOR



Vitramon Corporation

FIG. 3.21. CAPACITANCE/TEMPERATURE CHARACTERISTIC OF 820-pF TUBULAR CERAMIC CAPACITOR

readings, thermal lags are influencing the record. It is found that the lag is negligible when the rate of change of indicated temperature is less than 10°C per min. The source or sink of heat is slowly adjusted to stay below this limit. Recently, the samples have been encased in a capsule of silicone oil resulting in retrace curves which have no deviation when swept in two directions. During the cold cycles, consideration is given to frosting. The sample must be immune to moisture effects or the air in its vicinity must be desiccated.

Typical data obtained with this instrument are shown in Figs. 3.18–3.21.

Chapter 4

PAPER-DIELECTRIC CAPACITORS

In this chapter we shall consider in more detail the construction, behaviour and uses of various types of paper-dielectric capacitor (impregnated, metallized, castellated and pressurized types).

IMPREGNATED-PAPER CAPACITORS

Fixed tubular impregnated-paper capacitors are constructed by rolling paper insulation between metal electrodes. The electrodes are usually

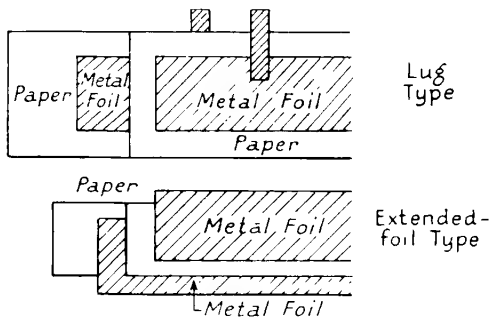


Fig. 4.1. End-connection Contacts to Foils

aluminium, but may be of tin or copper. The paper is made specially as capacitor tissue and is carefully dried and impregnated in wax or oil. The advantages of paper are that it is available in thin and strong self-supporting form, with good flexibility and fold endurance. It is insoluble in common solvents and has negligible cold flow. End-connection contacts to the metal-foil electrodes are basically of two kinds, the lug type or the extended-foil type, represented in Fig. 4.1. The construction of a typical metal-cased Neoprene-disc-sealed tubular capacitor and that of a larger rectangular metal-cased capacitor are shown in Fig. 4.2. For low-voltage operation in transistor circuits capacitors are often made with welded connections.

The paper is used in thicknesses which lie between 7·5 μm (0·0003 in.) and 25 μm (0·001 in.) and the foils used are about 0·00025 in. thick. The paper is made mainly from vegetable fibre chemically "digested" in strong alkali, resulting in cellulose in fibrous form. This

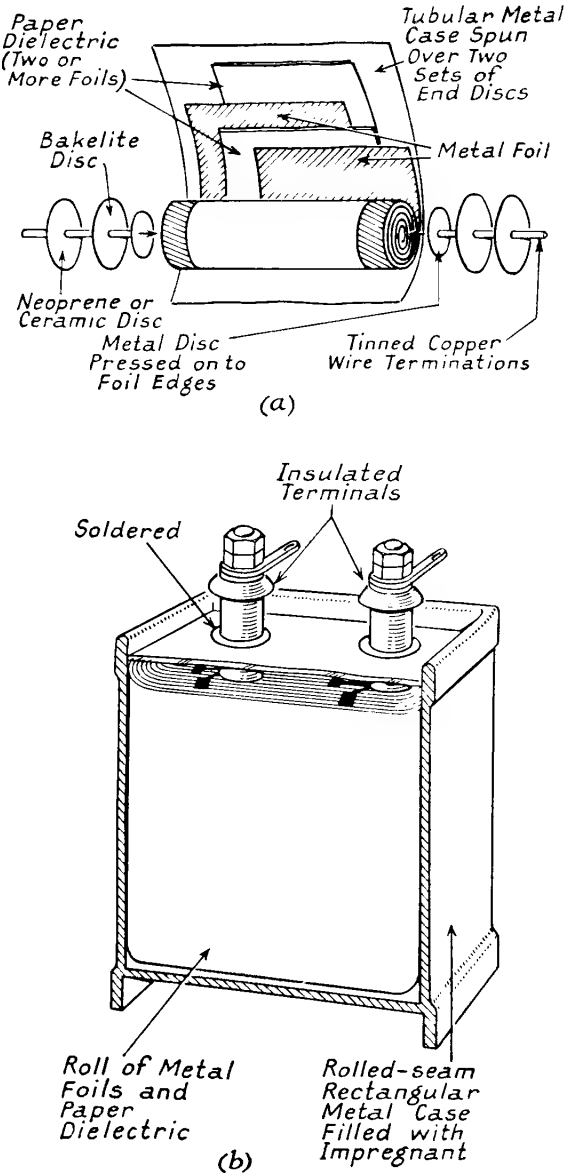


FIG. 4.2. CONSTRUCTION OF PAPER CAPACITORS

(*a*) Metal-cased Neoprene-disc-sealed tubular capacitor
(*b*) Larger rectangular metal-cased capacitor

pulp is then rolled into paper through warm rollers. Kraft or wood-pulp paper and linen paper are also used. All papers contain carbon particles which can project right through, particularly in the thinnest papers; metal impurities are also present at times. For this reason the minimum number of papers used is two, but there may be more, depending on the voltage rating and other characteristics of the capacitor being made. "Shives" or hard spots occasionally occur which will not take impregnation and which may contain impurities affecting the life of the capacitor. The working stress of impregnated paper as a dielectric is 15 to 25 V per micron, and papers of six to twelve microns thick are generally used in the United Kingdom. In Germany, Finland, France and the U.S.A., papers five microns thick are made. The actual breakdown or ultimate strength is about 150 V per micron, giving a safety factor of six. The voltage across one unit of foil and paper should never exceed 3 kV. All new paper is hygroscopic and contains from five to seven per cent of moisture. After drying, therefore, vacuum impregnation with mineral oils, paraffin waxes or petroleum jelly is necessary to fill up the voids left between the cellulose fibres of the paper. As these voids or air spaces are effectively in series with the cellulose, the effect of impregnation is to increase the permittivity of the dielectric, increase the power factor and increase the breakdown strength. Other impregnants of higher permittivity such as chloronaphthalene and chlordiphenyl are used to improve the permittivity and breakdown strength. Chloronaphthalene can be used for capacitors up to 200 to 300 V and temperatures up to 70°C. At high temperatures, failure may occur through deterioration of the paper as a result of its being attacked by hydrogen chloride formed from hydrogen generated by electrolysis and chlorine from the impregnants. The inclusion of a stabilizer such as azobenzene has been suggested by the E.R.A. to inhibit this deterioration by reason of its ability to accept hydrogen. Many tests have been made by the E.R.A., and the results show that long lives under d.c. stress at high temperatures, previously obtainable only with non-polar impregnants such as petroleum jelly, are possible with chloronaphthalene impregnants if 5 per cent of azobenzene is added.

Mineral oil is generally used for wider temperature ranges (from − 55°C to + 85°C), and capacitors impregnated with mineral oil have good capacitance stability with temperature changes. Castor oil can be used where the temperature range is restricted (− 25°C to + 65°C), with the advantage that a smaller capacitor can be made, as the permittivity of castor oil is comparatively high at low frequencies. Chlordiphenyl-impregnated capacitors have a permittivity which is dependent both on frequency and temperature. It is essential to maintain scrupulous cleanliness in the manufacture of chlordiphenyl-impregnated capacitors, as it is a powerful solvent and may absorb impurities

from such materials as rubber and certain metals such as copper (unless the copper is heavily plated).

In attempts to overcome the deficiencies of the chlorinated hydrocarbons as impregnants, many new types have been, and are still being, introduced. Amongst these are specially produced silicones, polyvinylcarbazoles and polyisobutylenes. Casting resins are also being used, both epoxy and polyester resins, and some plastic monomers such as styrene. The advantages and disadvantages of these as capacitor impregnants are discussed by L. Bursody.*

Kahn, in a paper entitled "Capacitors—1959"† gives a list of commonly used impregnants for paper capacitors which is reproduced as Table 4.1.

TABLE 4.1. CAPACITANCE CHARACTERISTICS OF COMMONLY USED IMPREGNANTS FOR PAPER

Material	Permittivity	Power factor	Resistivity (Ω-cm)	Capacitance (μF/mil)	Power factor (%)	*RC* product (Ω-F)
Mineral oil	2·23	0·03	10^{14}	600	0·20	20,000
Mineral wax	2·2	0·05	10^{15}	600	0·35	10,000
Petroleum jelly	2·2	0·05	10^{12}	600	0·35	10,000
Polyisobutylene	2·2	0·03	10^{15}	600	0·20	25,000
Silicone liquids	2·6	0·05	10^{16}	560	0·35	22,000
Castor oil	4·7	0·08	10^{12}	455	0·5	2,000
Chlorinated diphenyl	4.9	0·05	10^{13}	430	0·2	15,000
Chlorinated naphthalene	5·2	0·2	10^{11}	390	0·4	5,000

GENERAL CHARACTERISTICS OF IMPREGNATED-PAPER CAPACITORS

Capacitance Tolerances

The final capacitance of the manufactured capacitor may vary through causes such as variations in the following—

(1) Thickness of the paper used (may be ± 10 per cent).
(2) Density of the paper.
(3) Smoothness of the paper surface.
(4) Amount of metal foil used.
(5) Tension of winding.
(6) Characteristics of the impregnant used.

The overall tolerance of typical impregnated-paper capacitors is not usually better than ± 15 per cent.

Breakdown Voltage

There is a large difference between d.c. and a.c. breakdown voltages and the a.c. conditions are discussed on p. 85 in the paragraphs on

* *Trans. Inst. Radio Engrs.* **CP-7** (Mar., 1960), 15.
† *Trans. Inst. Radio Engrs.* **CP-6** (Sept., 1959), 150.

"The Behaviour of Paper Capacitors on A.C." The maximum d.c. or a.c. voltage which may be applied decreases with increase of temperature; e.g. at 100°C it may be only half the breakdown voltage at room temperature. In general, the losses in an impregnated-paper capacitor increase with increase of voltage, whilst the breakdown voltage decreases with increase of temperature. The ultimate breakdown strength of wax-, oil- and jelly-impregnated capacitors also depends a great deal on the time of application of the voltage. If the rate of increase of voltage is 50 V/min, the stress required to break down a good-quality capacitor paper is about two million volts (d.c.) per centimetre at room temperature; at 50°C it is one and a half million

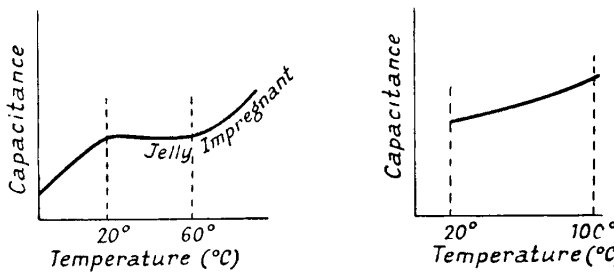


FIG. 4.3. CAPACITANCE VARIATION WITH TEMPERATURE FOR PAPER CAPACITORS: (*left*) RECTANGULAR TYPE, AND (*right*) TUBULAR TYPE

volts per centimetre, and at 80 C approximately one and a quarter million. On a.c. the peak breakdown voltage would be slightly less. With a steady voltage (either d.c. or a.c.) applied for twenty-four hours at room temperature, the stress required to break down the capacitor would be about half a million volts per centimetre.

Temperature Coefficient

This depends to a large extent on the shape of the capacitor and the nature of the impregnant. Cylindrical types wound on rigid formers are most satisfactory mechanically since the cylinder is an inherently rigid shape. The flat type (i.e. the cylinder squashed flat) usually has a higher temperature coefficient than the round type and may be non-cyclic. The temperature coefficients of both tubular and rectangular-cased types vary from about + 100 to + 200 ppm/ C, but that of the flat or rectangular-cased type is non-linear because the viscosity of the impregnant changes with temperature due to melting of the jelly. The temperature coefficient depends largely on the impregnant—with oil impregnants it is slightly positive over the range + 20 to + 60 °C, and with petroleum jelly it is slightly negative over the same range. Fig. 4.3 shows typical variations of capacitance with temperature. *See also* Table 4.1.

Permittivity

For capacitors impregnated with oil, wax or jelly, the permittivity is usually between 3·4 and 4·5. For a tubular capacitor where little winding pressure is used, the permittivity would be about 3·5. It is dependent also on the density of the paper; using heavy pressure and dense paper, the permittivity would be about 4·5. The permittivity rises slowly with increase of temperature and falls slowly with increase of frequency. For other impregnants *see* Table 4.1.

Power Factor or Loss Angle

For oil-, wax- and jelly-impregnated capacitors, power factor is also mainly dependent on the density of the paper; at 50 c/s it lies between 0·0015 and 0·003 for temperatures between 20°C and 60°C. The power factor decreases with increasing temperature and then rises again. At high temperatures the loss depends chiefly on the moisture impurities in the dielectric. The shape and position of the power-factor/temperature curve also vary with frequency. The power factor increases slowly with increase of frequency (the increase is rapid above 10 kc/s) but may fall again if the temperature is high—i.e. at high frequencies the maximum power factor occurs at a lower temperature.

Insulation Resistance or Resistivity

The insulation resistance of all paper-dielectric capacitors falls rapidly with increase of temperature, so that doubling the temperature, from 35° to 70°C, may result in the insulation resistance dropping to one-tenth of its original value. It depends critically on the moisture and impurity contents of the materials in the capacitor, and the effectiveness of the sealing is therefore of importance. Variations in value of over 1,000 to 1 are common between samples of commercial capacitors. Accurate measurements of resistivity must eliminate false readings due to surface leakage, and the graph in Fig. 4.4 (produced by the E.R.A.) shows the variation of resistivity with temperature, the conduction current in the paper being measured some time after all absorption current has ceased. Conventional readings taken without guard rings and without great precautions may result in measurements at least ten times lower than these figures.

The results of some measurements showing the variation of insulation resistance with temperature for typical paper-dielectric capacitors, are given in Chapter 2, on p. 23.

The Behaviour of Paper-dielectric Capacitors on A.C.

When an alternating voltage is applied to a capacitor the foils are alternately positive and negative, and therefore attract one another, so

that there is mechanical as well as electrical stress. The plates tend to become squashed together as the voltage increases and the capacitance increases in consequence. With oil-filled capacitors this effect is marked, with jellies it is less so, while with viscous or solid dielectrics it is comparatively small.

The maximum peak a.c. voltage which should be applied to a

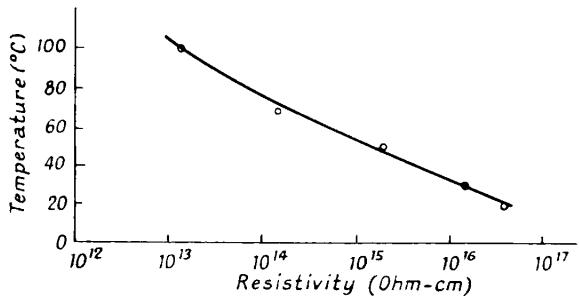


FIG. 4.4. VARIATION OF RESISTIVITY WITH TEMPERATURE OF PAPER DIELECTRIC

tubular impregnated-paper capacitor is limited to about 350 V. This is because some air bubbles are always left in the impregnated paper, even after vacuum impregnation at 0·5 mm of mercury for 50 hr. On

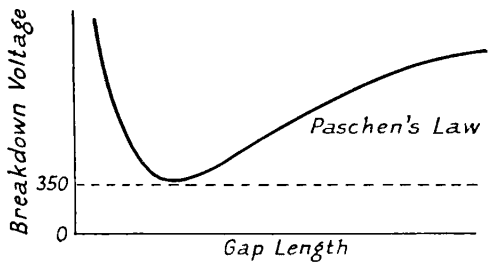


FIG. 4.5. BREAKDOWN OF AIR WITH GAP LENGTH

a.c. these bubbles ionize, glow discharge takes place and the surrounding paper is burnt. With a.c. this occurs on each cycle, and is therefore serious. On d.c. it occurs only at the moments of switching on and off, although ionization will occur with steady d.c. if the voltage is high enough. There are two approaches to this problem—either the vacuum can be increased still more during impregnation (which is expensive and impracticable) or the air can be prevented from ionizing by reducing the voltage across the air bubbles. If a curve is plotted of breakdown voltage against gap length in air, the Paschen's curve of Fig. 4.5 results.

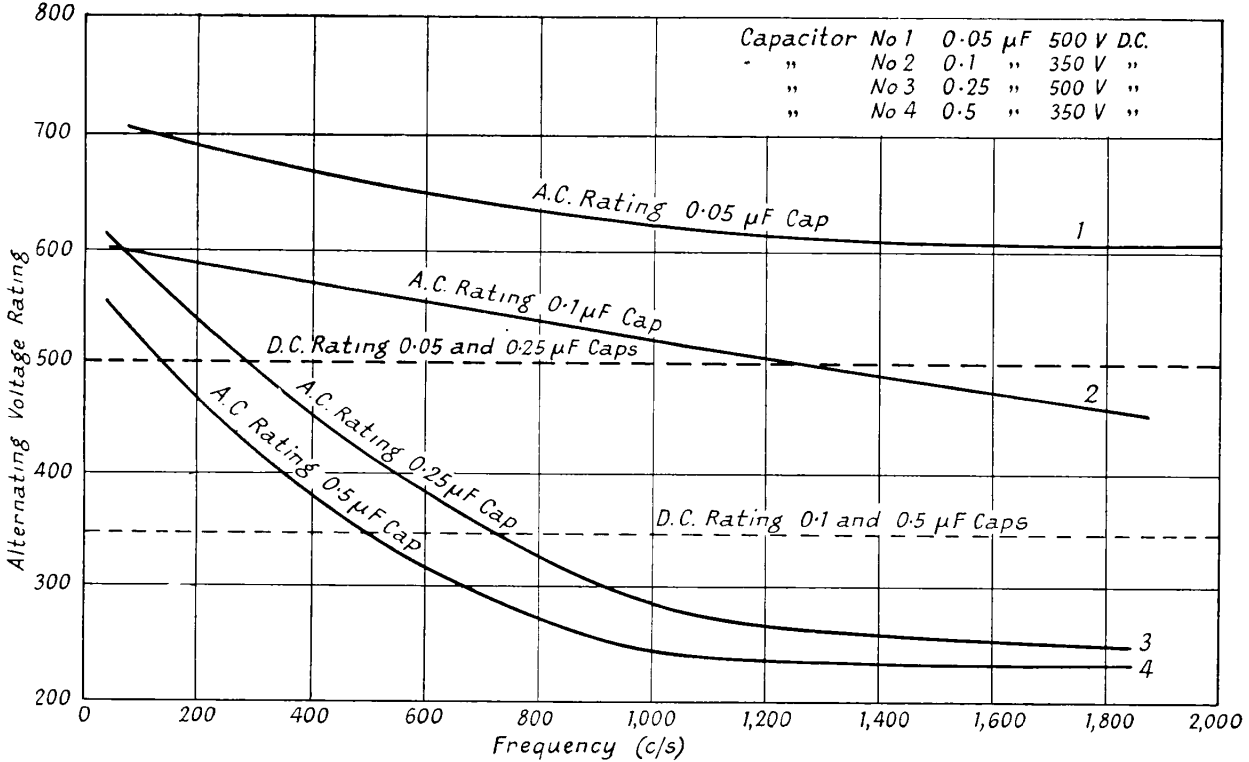


FIG. 4.6. A.C./D.C. RATINGS OF SMALL PAPER CAPACITORS AT LOW FREQUENCIES

It is seen that there is a definite minimum voltage below which breakdown does not take place, regardless of gap length. This is about 350 V for air (for neon it is about 120 V). Ionization is not, however, synonymous with breakdown. In air, ionization can occur continuously and stably, as for example in h.t. lines and cables. In a capacitor it is the ionization in air voids which reduces the life, due to local overheating and erosion of the dielectric. The peak voltage across the capacitor elements should, therefore, never be more than 350 V on a.c. Capacitors for operation at higher a.c. voltages are specially made, using series sections and oil impregnation free from voids. In practice, a factor of safety is provided by the fact that the discharge requires a voltage slightly higher than 350 V to actually strike. The behaviour of typical small tubular paper-dielectric capacitors at frequencies up to 2,000 c/s is shown in Fig. 4.6.

This figure shows that at a frequency of 50 c/s the alternating-voltage rating is greater than the direct-voltage rating, but as the frequency is increased the maximum alternating voltage which the capacitor will withstand becomes very much reduced. This reduction is greater for the higher capacitance values. This is partly due to the excessive heating when larger currents flow at high frequencies, the current being proportional to $E/X_c = \omega CE = 2\pi fCE$, and partly due to the greater damage resulting from discharges at the higher frequencies. Referring to the diagram, the relation between the a.c. rating and the frequency is seen to be practically linear for the capacitors of values 0·5 and 0·1 μF, but for the higher capacitance values the curve tends to become asymptotic to a value of about 265 V for a capacitance of 0·25 μF, and 250 V for 0·5 μF.

The Behaviour of Paper-dielectric Capacitors at Radio Frequencies

The tubular types of paper capacitor are the only ones likely to be used in r.f. circuits, and the inductance of such a capacitor is taken as equivalent to that of a straight length of 20 s.w.g. copper wire equal in length to the capacitor, including connecting wires. This inductance will be between about 0·01 and 0·05 μH. In r.f. filters, the self-inductance of the capacitor may be used to resonate at some particular frequency, and the reduction in impedance under such conditions is shown in Fig. 4.7.

METALLIZED-PAPER CAPACITORS

One side of the paper tissue can be sprayed with metal, or metal can be evaporated onto the tissue. This has the advantage that the electrode is as thin as possible and when rolled the capacitance for a given volume is higher than that of the normal foil-and-paper types.

With the exception of a small distance from one edge, the entire width of one side of the paper can be metallized, leaving a narrow band of unmetallized tissue along one edge of its length. The actual width of

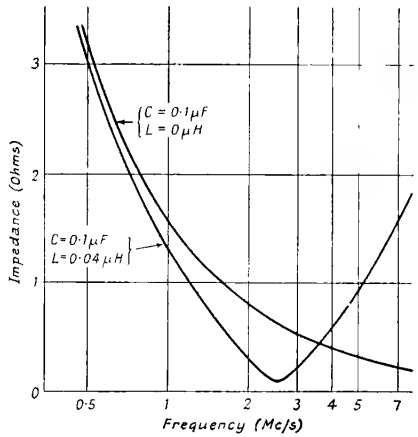


FIG. 4.7. EFFECT OF RESIDUAL INDUCTANCE ON IMPEDANCE OF 0·1-μF CAPACITOR

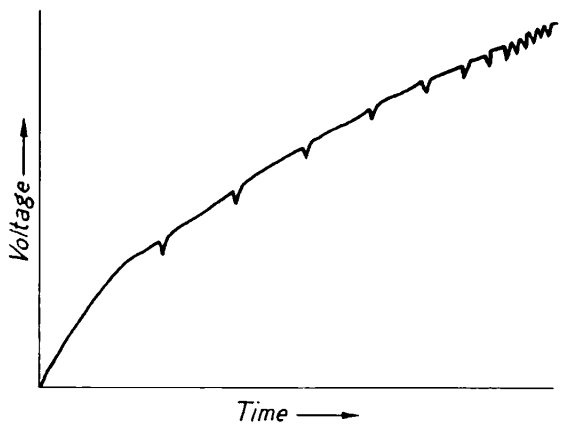


FIG. 4.8. MOMENTARY BREAKDOWN OF METALLIZED-PAPER CAPACITOR WITH INCREASING VOLTAGE

this band is determined by the working voltage of the capacitor. The most important property of this type of capacitor, apart from its small size, is its property of self-healing under slight excess voltage. If the voltage across the capacitor is gradually raised a value will be reached at which sparking occurs, and if the voltage is maintained at

this value the sparking will only be momentary. This sparking occurs at points of dielectric weakness in the paper, and the thin metal film is evaporated from these spots without damaging the paper. With aluminium film the high temperature will produce aluminium oxide, which is itself a good insulator. The electric strength of the paper dielectric will therefore be restored almost immediately. The voltage

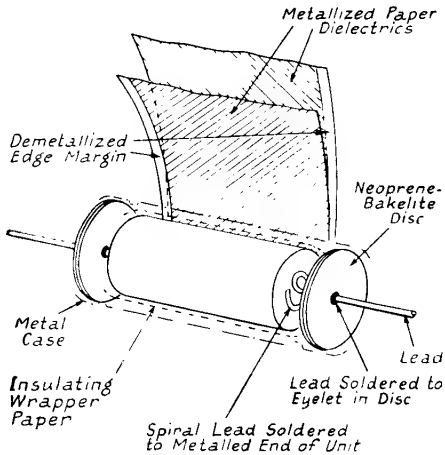
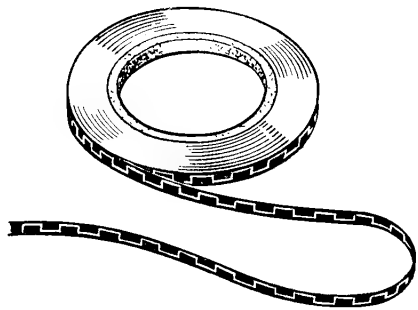


FIG. 4.9. CONSTRUCTION OF TUBULAR METALLIZED-PAPER CAPACITOR

can then be increased to a higher value, when further momentary sparking will occur (*see* Fig. 4.8). A point is finallly reached when sparking becomes continuous and breakdown occurs. The maximum voltage at which this self-healing action will occur without detriment to the properties of the capacitor is termed the *test voltage* and is approximately 1·5 times the working voltage. The maximum short-term voltage (applied for less than 10 sec) which can be applied without destroying the capacitor is termed the *spark voltage* and is approximately 1·75 times the working voltage. Care must, therefore, be taken to ensure that metallized-paper capacitors are not subjected to continuous voltage overloading.

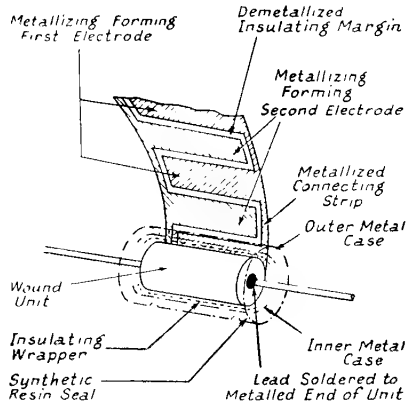
More recent types of metallized-paper capacitors use a lacquered paper tissue on which aluminium has been evaporated in a vacuum. The coating is extremely thin and is of the order of 0·000004 in. The metallized tissue is passed between metal rollers across which the working voltage of the capacitor is applied to remove any weak points, as described previously. Two tissues are superimposed so that the metallized edge of one tissue lies over the unmetallized edge of the other and

the tissues are then wound into a roll. As the unmetallized part of the tissue serves as an insulator between the two electrodes, no other tissue is required. Each end of the roll is then sprayed with copper to enable the edges to be connected together and wires attached. The construction of a typical tubular metallized-paper dielectric capacitor is shown in Fig. 4.9.



A. H. Hunt, Ltd.

FIG. 4.10. "CASTELLATED" METALLIZED PAPER



A. H. Hunt, Ltd.

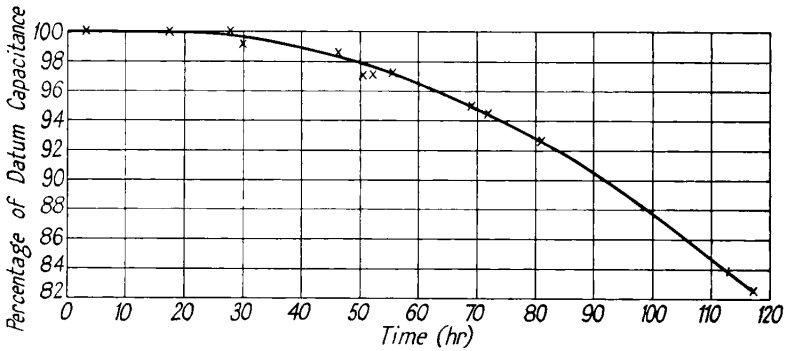
FIG. 4.11. CONSTRUCTION OF "CASTELLATED" PAPER CAPACITOR

Castellated Metallized-paper Capacitors

A further development is the "castellated" technique developed by Messrs. A. H. Hunt, Ltd., which uses one paper to provide dielectric and both electrodes. A castellated insulating track along the aluminized paper is produced as shown in Fig. 4.10. It is arranged that each metal tongue corresponds to an exact circumference; as the diameter of the winding increases, the tongue length increases. This method produces

an extremely compact capacitor; the internal construction is shown in Fig. 4.11.

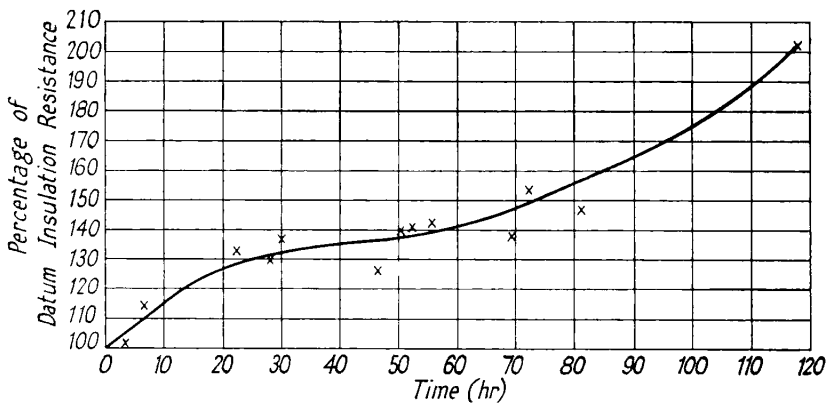
For the Hunt W97 type, the normal temperature rating is — 40°C to



A. H. Hunt Ltd.

FIG. 4.12. CAPACITANCE/TIME CHARACTERISTIC OF 0·04-μF 150-V D.C. CAPACITORS

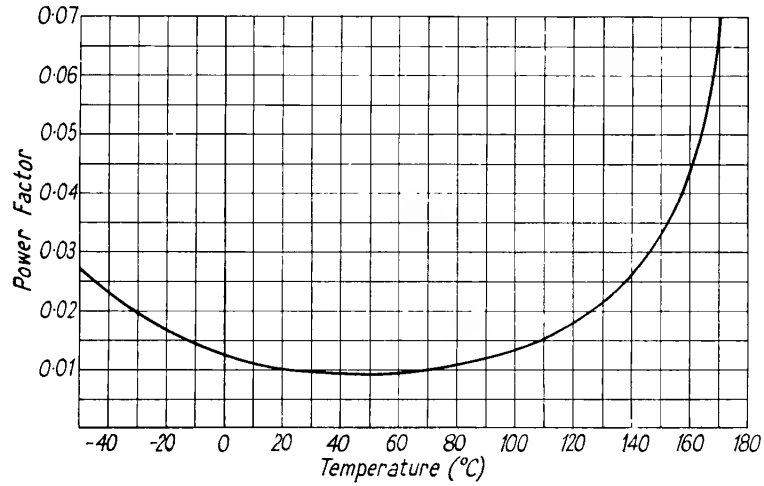
+ 100°C, but experimental work has shown these capacitors to be capable of operating at higher temperatures with a correspondingly shorter life. There is a fall in capacitance with increasing temperatures,



A. H. Hunt Ltd.

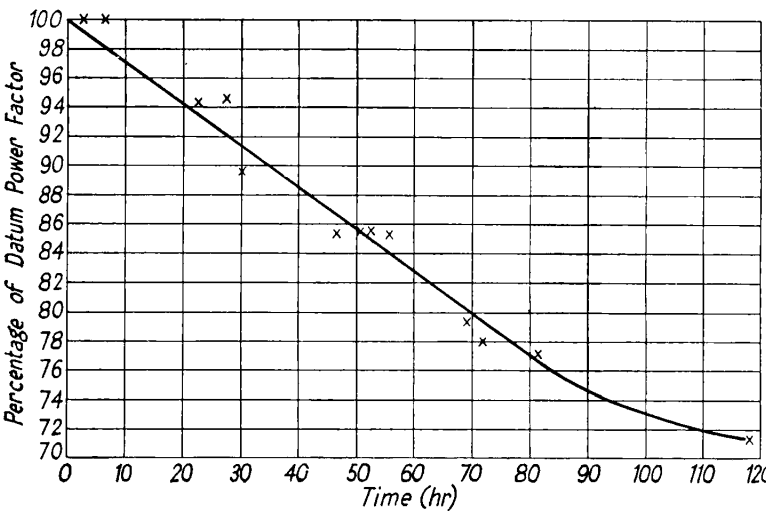
FIG. 4.13. INSULATION-RESISTANCE/TIME CHARACTERISTIC OF 0·04-μF 150-V D.C. CAPACITORS

but an improvement in both insulation resistance and power factor. For a batch of 20 samples operated at 150 C for over 100 hr the fall in capacitance is shown in Fig. 4.12, the increase in insulation resistance in Fig. 4.13, and the fall in power factor in Fig. 4.14. A



A. H. Hunt Ltd.

FIG. 4.14. POWER-FACTOR/TIME CHARACTERISTIC OF 0·04-μF 150-V D.C. CAPACITORS



A. H. Hunt Ltd.

FIG. 4.15. POWER-FACTOR/TEMPERATURE CHARACTERISTIC OF CAPACITORS OF FIGS. 4.12–4.14

complete curve of power factor variation with temperature from — 40°C to + 170°C is shown in Fig. 4.15.

General Characteristics of Metallized-paper Capacitors

The *RC* product of this type of capacitor (with the exception of the W97 type made by Messrs. A. H. Hunt, Ltd.) is lower than that of the normal foil-and-paper capacitor. With the working voltage applied, it is of the order of 100 Ω-F. The working temperature range is between — 30°C and + 70°C, although it is possible to operate these capacitors up to 85°C with derating. This applies to the types normally impregnated with petroleum jelly and wax coated, but recent types with polyester resin impregnation and ethoxylene resin sealing have greater working temperature ranges and can be operated up to 125°C. Capacitance tolerances are of the order of ± 25 per cent and capacitance stabilities under normal conditions about ± 5 per cent. The power factor is about 0·02 to 0·05. The self-inductance is low and approximately equivalent to that of a solid piece of metal of the same size and shape as the capacitor.

The main mechanism of long-term failure of paper-dielectric capacitors under d.c. stress is electrochemical deterioration, either from excessive electric stress at a point or excessive ionic impurity.

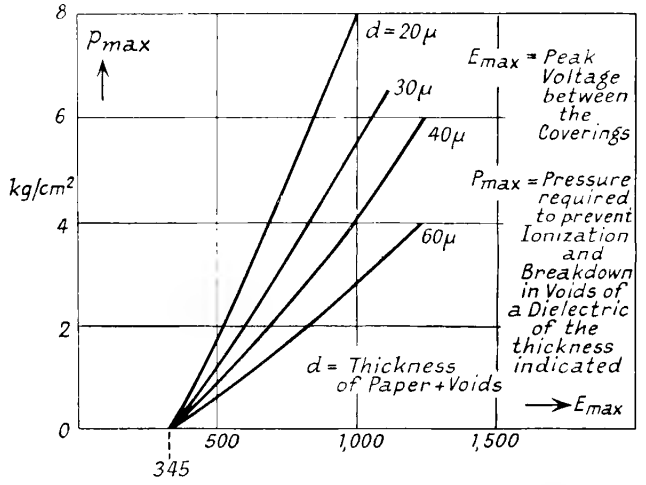
In metallized dielectrics, these weak points are the ones which are removed initially by "burning-out" at two to three times the rated voltage. Although normally self-healing, metallized-paper capacitors may become faulty (drop in insulation resistance) when used in series with a high resistance, e.g. 1 MΩ on a 100-V supply.

PRESSURIZED-PAPER CAPACITORS

Large paper-dielectric capacitors are used for power-factor correction in industrial electrical systems, collieries, etc. It is possible by pressurizing these large capacitors to increase the working voltage considerably and still maintain their reliability. Breakdown is usually caused by ionization of voids in the paper tissue, resulting in overheating and carbonization at these spots with consequent failure of insulation. The voltage at which breakdown occurs in air is given by Paschen's curve, shown on p. 86. Fig. 4.16 shows the increase in working a.c. voltages by pressurizing, for different thicknesses of paper.

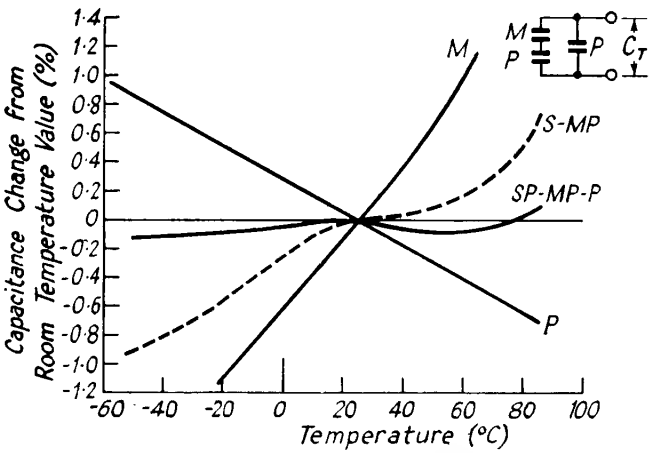
CAPACITORS WITH MIXED PAPER AND OTHER DIELECTRICS

Often, no single dielectric will meet a particular requirement, and combined dielectrics can be used to meet specific temperature-coefficient or wider temperature-characteristic requirements. Capacitors are now available using a combination of dielectrics, e.g. paper and polystyrene, paper and Melinex, paper and P.T.F.E., etc.



Philips Ltd., Eindhoven

FIG. 4.16. INCREASE IN WORKING VOLTAGE OBTAINED BY PRESSURIZING



Condenser Products Co.

FIG. 4.17. CAPACITANCE/TEMPERATURE CHARACTERISTICS OF SERIES-PARALLEL CAPACITOR USING MELINEX AND POLYSTYRENE (AT 1 KC/S)

S-MP. Equivalent series Melinex-polystyrene capacitor in parallel with polystyrene capacitor, 1:1 capacitance ratio
M. Melinex
P. Polystyrene

Combinations of paper and Melinex film can give an appreciable increase in the life of a capacitor (estimated up to 10 times) with an increase of insulation resistance particularly at the higher temperatures. Combinations of polystyrene with other film materials enable flatter temperature characteristics and higher operating temperatures to be obtained with polystyrene alone.

To eliminate the need for paralleling separate capacitors, the Condenser Products Co., Connecticut, U.S.A., has developed methods of winding laminates of two or even three different films in a single concentric unit. This type of construction provides a large variety of high capacitances and temperature coefficients over wide temperature ranges. For example, Fig. 4.17 shows the capacitance change *v.* temperature for double-layer wound Melinex/polystyrene units such that the unit is equivalent to a series-connected Melinex and polystyrene capacitor in parallel with a polystyrene capacitor. With proper processing the units will have a room temperature stability of the order of 0·1 per cent and a maximum capacitance change of less than 0·25 per cent over a temperature range of − 70°C to + 75°C.

By a similar winding method P.T.F.E. and fibre-glass impregnated P.T.F.E. can be processed to yield an overall capacitance change of 1 per cent over the temperature range − 70° to + 200° C.

CHAPTER 5

MICA-DIELECTRIC CAPACITORS

MICA occurs naturally, mainly in India (Bengal and Madras), Canada and South America. It is found in laminated masses which are capable of being split or separated into sheets. This property of cleavage is due to the particular crystal structure and is the most important property of mica for electrical usage. For use in capacitors it is usually split down to about 0·002 in.; below this, wastage may become serious. It is possible by special laboratory techniques to split to about 0·00001 in.

The micas are very complex and variable in their chemical composition, but all are silicates, usually orthosilicates, of aluminium, together with alkali metals and basic hydrogen, with other metals, e.g. magnesium and iron, and sometimes fluorine. They are very inert, muscovite being attacked only by hydrofluoric acid. Phlogopite is affected by sulphuric acid. The micas are non-hygroscopic.

There are many types of mica, and only the commonest are mentioned here. The qualities of a type may vary widely.

Muscovite (*White Mica*). This is the commonest form, much of which is colourless and transparent. It has the greatest mechanical strength and a maximum working temperature of about 500°C. Above 600°C it begins to calcine. It is widely used for electrical insulation.

Ruby Mica (*Rose-coloured Mica*). A variety of muscovite. The highest quality has the best dielectric properties. It is widely used for insulation and particularly for capacitor dielectrics.

Phlogopite (*Amber Mica*). Softer than muscovite, but with a higher maximum working temperature (900 to 1,000 C). It is often used in armature construction. Its dielectric properties are inferior to those of good muscovite.

Biotite (*Iron Mica* or *Black Mica*). Its electrical properties are inferior to those of muscovite, but it is used for general insulation.

Vermiculite. This name covers a group of hydrous silicates occurring as decomposition products of the micas. They are mainly hydrated silicates of aluminium, iron and magnesium. When heated slowly, they exfoliate and open into long worm-like threads.

The electrical properties of mica vary according to the place of origin and are approximately as in Table 5.1, although it should be remembered that these figures depend on the dryness of the specimen and on the method of testing.

The power factor of mica varies considerably, from 0·02 to 0·0002,

but can be as low as 0·00005 if specially selected and dry. The specific gravity varies from 2·7 to 3·2. It should be borne in mind that the insulating value of mica deteriorates with heat (commencing, with poor specimens, at about 400 C), as a result of delamination due to dehydration. Mica, being a natural material, also contains impurities which will vary according to the source of supply. In processing mica for

TABLE 5.1

Origin	Resistivity (Ω-cm)	Permittivity	Disruptive strength (V/mm)
	$\times 10^{12}$		
Bengal	15 to 133	2·5 to 7·0	50,000 to 80,000
Madras	7 to 118	2·8 to 7·0	40,000 to 120,000
Canada	0·44 to 22	2·9 to 3·0	70,000 to 90,000
S. America	37 to 40	5·8 to 6·0	40,000 to 90,000

capacitors and for other applications, a number of terms are used which are defined below.

"Crude" mica is the crude crystals or "books" as extracted from the mine.

"Cobbing" is the process of removing dirt, rock and mine scrap from crude mica.

"Rifting" is the process of splitting cobbed mica into sheets of suitable thicknesses.

"Trimming" or "dressing" is the process of removing major flaws in rifted mica, using fingers, sickle, knife, shear or guillotine, and the mica is called "thumb-trimmed" mica, "sickle-trimmed" mica, etc. "Full-trimmed" mica is trimmed on all sides, with all cracks and cross-grains removed. "Half-trimmed" mica is trimmed on two sides only.

"Blocks" of mica are 0·007 in. minimum thickness, full-trimmed.

"Book-form" splittings are in the form of individual books or bunches, each book comprising consecutive splittings obtained from the same piece of block mica. Book-form splittings are generally dusted with mica powder to offset residual cohesive forces.

"Thins" are knife-dressed mica plates at least 0·002 in. but less than 0·007 in. in thickness.

"Scrap mica" is the name given to by-products obtained in the course of processing different grades of mica.

"Hard mica" is mica which does not show any tendency to delaminate when slightly flexed or distorted with thumb pressure. Thick pieces of this mica will give an almost metallic sound when tapped or dropped on a hard surface.

For use in capacitors, the full-trimmed mica is graded for size and

quality by visual examination; it falls into blocks varying from 1 in. square or less to a maximum of about 5 to 6 in. It is usually tested electrically in two ways—testing for conducting particles or pinholes by a form of high-frequency spark, and testing the Q-factor. It is also examined for imperfections such as spots, stains, cracks, hairlines, holes and air inclusions. The American A.S.T.M. Specification D.748/52T divides mica, as a capacitor dielectric, into three classes—*Class C1* block mica or mica film has the highest Q-factor obtainable for mica (a minimum of 2,500 at 1 Mc/s in capacitors) and is suitable for use with all sizes and types of silver and foil electrodes in high-stability tuned circuits as well as transmitter capacitors. Class C1 mica also has

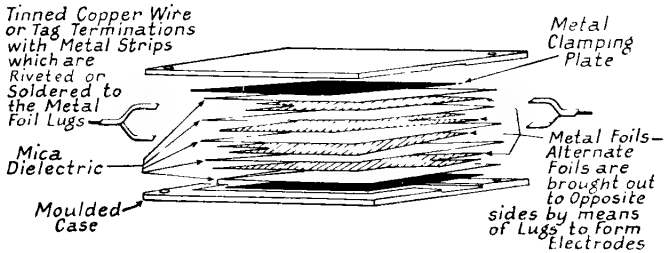

Tinned Copper Wire or Tag Terminations with Metal Strips which are Riveted or Soldered to the Metal Foil Lugs
Mica Dielectric
Moulded Case
Metal Clamping Plate
Metal Foils—Alternate Foils are brought out to Opposite sides by means of Lugs to form Electrodes

FIG. 5.1. CONSTRUCTION OF A STACKED-MICA CAPACITOR

the highest Q obtainable in the audio-frequency range—a minimum of 1,000 at 1 kc/s. *Class C2* is suitable for general use and has a minimum Q of 1,500 at 1 Mc/s in capacitors. The temperature rise in transmitter types is higher than for C1 mica capacitors. *Class C3* block mica and mica film has the lowest Q —200 at 1 Mc/s in capacitors—and is suitable for use in foil-electrode moulded and clamped-type capacitors.

STACKED-MICA CAPACITORS (STACKED FOIL AND MICA)

Mica, prepared as described above, is tested and cut to the required size. The sheets are then interleaved with electrodes of brass, tin, or copper foil, and the assembly is held together in a clamp to maintain rigidity of the foils. The construction of a typical stacked-mica foil capacitor is shown in Fig. 5.1.

The lead-out contacts are usually attached by spot welding, which also connects the foils of similar polarity where a number of foils are involved. It is essential that a reliable noise-free contact should be made to the foils. The assembly is then often moulded in a plastic case to protect it from mechanical damage and as a partial seal. Some units are then wax treated to minimize moisture penetration and also to reduce the leakage across the surface. Other units are impregnated with high-melting-point wax only.

The type of encasing employed for mica-dielectric capacitors is important, as the dielectric leakage and temperature limitations of encasing materials often restrict the performance of the capacitor. Both stacked- and silvered-mica capacitors are very susceptible to the effects of moisture, and the power factor will increase severely if moisture is allowed to penetrate the case. As the permittivity of water is high (approximately 80), comparatively small quantities will lower the insulation resistance, increase the power factor and increase the capacitance. Thorough protection by sealing is therefore essential. Various plastic and other materials have been and are being used, amongst them the following—

(1) Wax.
(2) Moulded loaded phenol formaldehyde (Bakelite,* etc.).
(3) Moulded loaded and unloaded ethoxylene resins (Araldite,* etc.).
(4) Moulded Polythene* with compressed rubber lead-out seals.
(5) Cases of ceramic, glass, Mycalex,* etc., with soldered seals.
(6) Cases of ceramic, glass, Mycalex, etc., sealed with Araldite, etc.

Apart from molecular penetration through the encasing material, moisture penetration occurs along the lead-out wires. For a good seal, therefore, the material must either "wet" the metal, or a flexible bung must be compressed round the leads, or a ceramic or glass casing with end-soldered joints may be used.

The main use of stacked-mica capacitors is as coupling capacitors, etc., in r.f. circuits, because of their low inductance and low power factor. They are capable of carrying appreciable r.f. currents and are, therefore, used as transmitter capacitors. There is no intrinsic upper frequency limit for stacked-mica capacitors, but lead lengths, losses over casing, etc., usually set practical limits, as discussed in Chapter 2 (p. 25). Difficulty is sometimes experienced in specifying temperature coefficients accurately owing to the method of construction and the changes in quality of the mica now being mined, but the total variation with temperature of the element, uncased, can be specified within narrow limits. Most mica capacitors produced commercially have appreciable mechanical pressure applied to the dielectric. This may arise from the clamping of the stacked unit during assembly and/or the process of moulding. Measurements show that the effect of pressure is to increase both the temperature coefficient and the absolute capacitance of the capacitor. As the pressure varies with temperature, due to the relative thermal expansions of the various materials used in construction, the complete capacitor exhibits a complex and non-linear variation of capacitance with temperature.

* Registered trade mark.

Precision sealed mica-dielectric capacitors have been used at room temperature as sub-standards for many years. Their performance was summarized by Garton in 1946 (*see* Bibliography, p. 237). As an example of the stability of precision mica capacitors the National

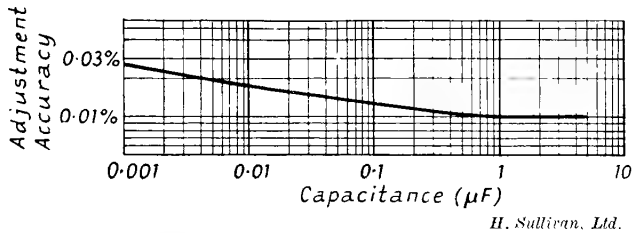


FIG. 5.2. ADJUSTMENT ACCURACY OF PRECISION MICA CAPACITORS

Physical Laboratory took a twenty-year-old capacitor, dried it in a desiccator at 65 per cent R.H. for one year, then sealed it in a brass case fitted with glass/metal seals. After sealing, the capacitance remained constant at 10,054 pF within ± 0·2 pF over a test period of 10,000 hr.

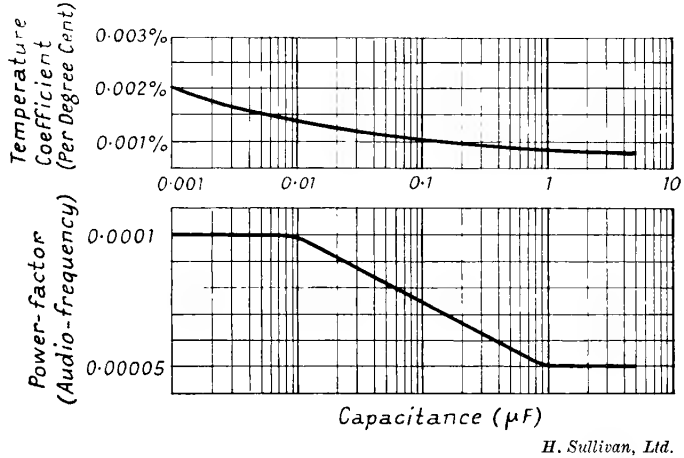


FIG. 5.3. PRECISION MICA CAPACITOR CHARACTERISTICS

The power factor before sealing was 0·0006, and after drying and sealing was reduced to 0·0001, remaining constant at that value (*see* Bibliography, p. 238, Rayner and Ford). Commercially produced mica sub-standards are available which can be adjusted to an accuracy shown in Fig. 5.2. In this diagram logarithmic scales of capacitance have been adopted to accommodate the wide range of values involved.

The variations of temperature coefficient and of power factor at audio frequencies for precision laboratory types of mica capacitor are shown in Fig. 5.3.

SILVERED-MICA CAPACITORS (METALLIZED-MICA CAPACITORS)

Silvering the mica sheets has the advantage of eliminating voids between sheet and foil and results in improved stability and reduced size. The mica sheets are tested and cut to size in a similar manner as for stacked-plate types. A silvering solution is prepared, consisting of silver oxide powder in rosemary, or lavender oil, and coated on the

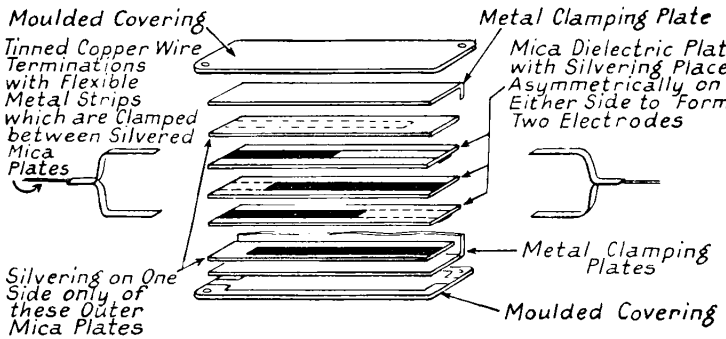
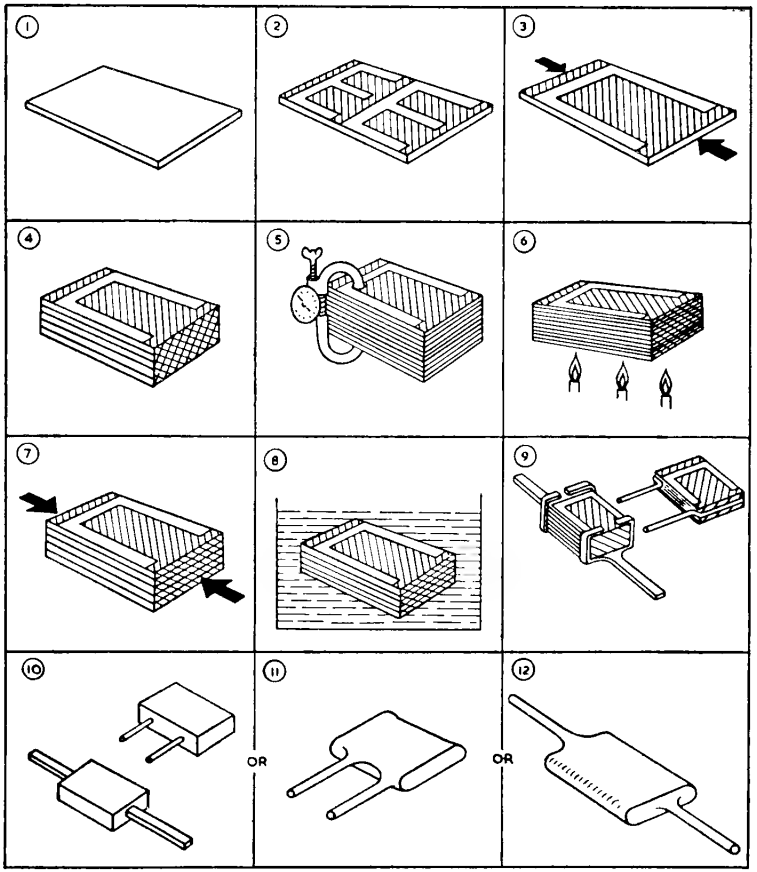

Moulded Covering
Tinned Copper Wire Terminations with Flexible Metal Strips which are Clamped between Silvered Mica Plates
Metal Clamping Plate
Mica Dielectric Plates with Silvering Placed Asymmetrically on Either Side to Form Two Electrodes
Metal Clamping Plates
Silvering on One Side only of these Outer Mica Plates
Moulded Covering

FIG. 5.4. CONSTRUCTION OF A SILVERED-MICA CAPACITOR

clean mica surface. The sheets are then fired in an oven at about 400° to 500°C. This volatilizes the oil and reduces the oxide to silver. Methods of placing the silvering paste on the mica plates vary; squeegeeing through a silk-screen pattern or offset printing methods can be used, the mica plates being held in suction clips during the process. The plates are usually silvered asymmetrically on both sides, and over the ends, and stacked alternately (*see* Fig. 5.4). Leads are soldered on to each end of the stack, although generally small pieces of brass foil are interleaved to make better contact with the silver electrodes (Fig. 5.4). Each capacitor can be accurately adjusted to the required value by removing small areas of the silver.

The process of manufacture is very similar to that described for stacked-mica electrodes. The required number of silvered-mica sheets (for the total capacitance needed) are placed in a special clamp with foil connections making contact with the silver film. This clamp has a window through which a portion of the film may be removed to adjust the capacitance. Terminal wires are soldered to the foils and the unit is then impregnated, usually with wax, to prevent the moulding material



Standard Telephones and Cables Ltd.

FIG. 5.5. SEQUENCE OF OPERATIONS IN MANUFACTURE OF SILVERED-MICA CAPACITOR

1. Mica plate, 0·001 in. or 0·003 in.
2. Mica plates printed with silver paste, and fired
3. Cut to size, and silvered edges reinforced with silver paste
4. Stacked into 5-plate stacks
5. Five-plate stacks and single plates used to make stacks of required size using a comparator
6. Stacks fired at 600°C
7. Silvered edges reinforced with silver paste
8. Impregnation
9. Axial or radial terminal wires soldered onto stack, adjusted to capacitance
10. Resin moulded
11. Resin dipped
12. Wax dipped

affecting the silver. It is then moulded into a cover of loaded phenol-formaldehyde, or other material, such as is used for stacked types. The construction of a typical capacitor is shown in Fig. 5.4, whilst the sequence of operations used by one particular manufacturer is shown in Fig. 5.5.

The main uses of silvered-mica capacitors are as padding capacitors in tuned r.f. circuits, because they can be accurately adjusted by the

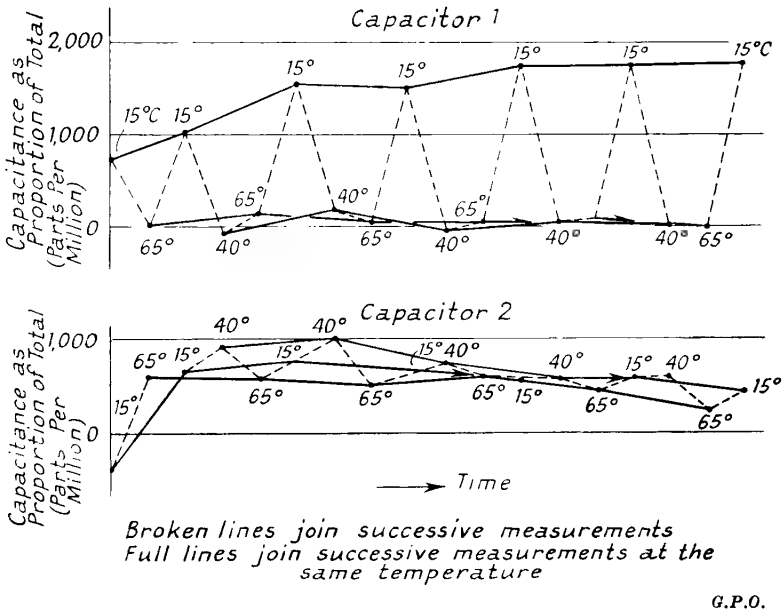


FIG. 5.6. CURVES SHOWING TYPICAL CHANGES OF CAPACITANCE WITH TEMPERATURE FOR SILVERED-MICA CAPACITORS

manufacturers to required capacitance values. Capacitors are made to tolerances of ± 20, ± 10, ± 5, ± 2 and ± 1 per cent, with a minimum of 1 pF. The variation of capacitance with temperature for typical capacitors is shown in Figs. 5.6 and 5.7.

Typical temperature-coefficient measurements on moulded silvered-mica capacitors are shown in Fig. 5.8.

A spread of temperature coefficient from + 300 ppm/°C to − 200 ppm/°C has been recorded, and precise values cannot be predicted even when any specific method of construction is used.

By measuring the temperature coefficient of the capacitor during assembly and adding a small quantity of silicone grease between the

plates, it is possible to adjust to any desired value. This technique would, of course, be used only for special requirements.

With rapid rises in temperature there is an equally rapid fall in insulation resistance. Several interesting tests have been made at temperatures above the normal working temperature (up to 200°C).

Experimental tests were carried out with two different rates of heating. In each test three specimens were mounted in the oven and

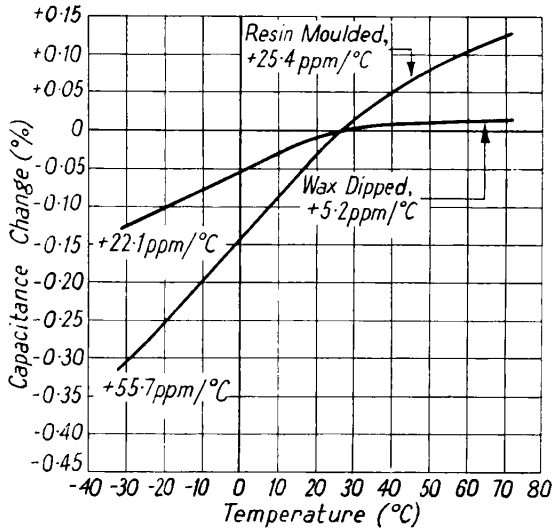


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FIG. 5.7. CAPACITANCE/TEMPERATURE CHARACTERISTICS OF SILVERED-MICA CAPACITORS

the insulation resistances were measured at room temperature. In the first test the temperature was raised to 200°C in 20 min with insulation-resistance measurements made at 5-min intervals, and the temperature then maintained for approximately 32 hr with readings taken at longer intervals. For the second test the period of temperature increase was extended to 100 min with insulation-resistance measurements made every 10 min followed by a period of approximately 24 hr at 200°C with insulation-resistance readings at longer intervals.

The average results were plotted, as shown in Fig. 5.9, from which it will be seen that after 200°C was attained the curves were almost coincident. If it is assumed that this would occur for other rates of

temperature increase then the minimum insulation resistance would lie approximately on this line (XY). Thus the minimum insulation resistance for a temperature increase period of 1 min would be between 15 and 20 MΩ.

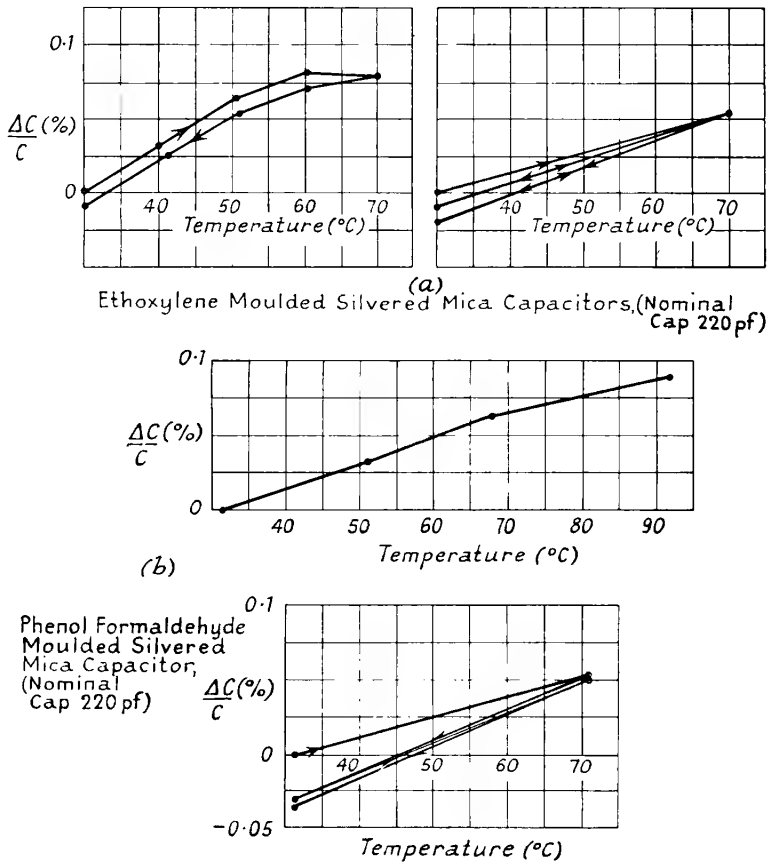

FIG. 5.8. TYPICAL TEMPERATURE-COEFFICIENT MEASUREMENTS ON MICA CAPACITORS

The increase in power factor or loss angle with increasing temperature for wax-dipped resin-moulded capacitors is shown in Fig. 5.10. The decrease in insulation resistance with increasing temperature for similar types of capacitor is shown in Fig. 5.11. The importance of moisture resistance of the capacitor covering has already been

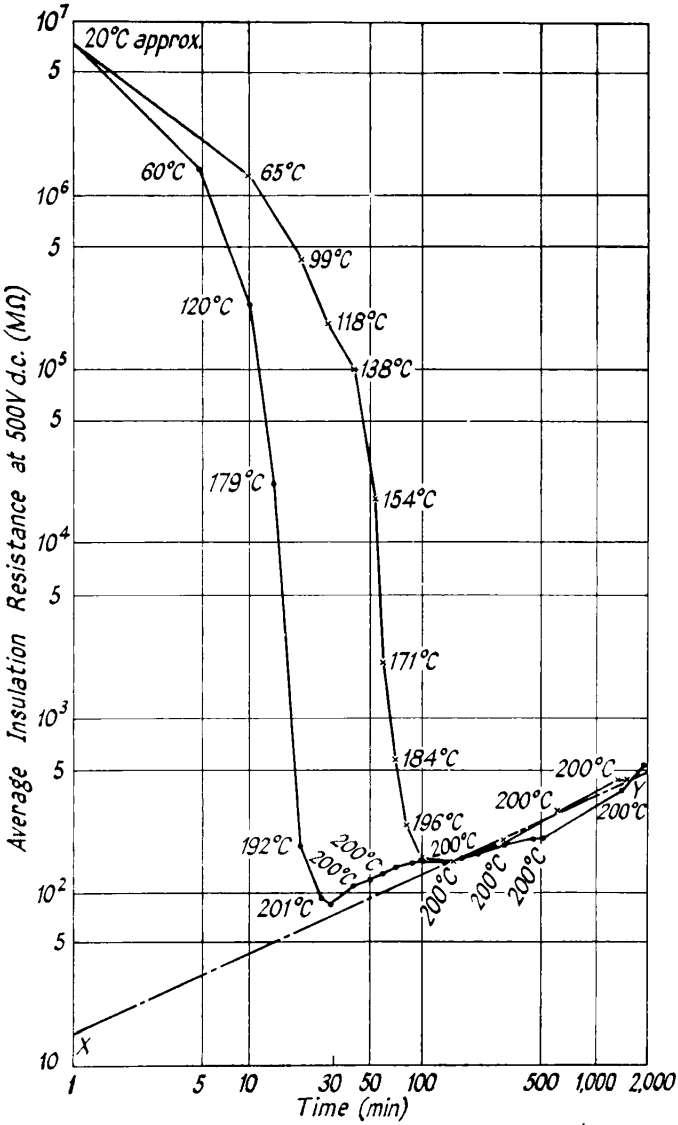

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FIG. 5.9. CHANGE IN INSULATION RESISTANCE WITH VARYING RATES OF INCREASE OF TEMPERATURE: 470-pF 750-V D.C. (WORKING) CAPACITORS

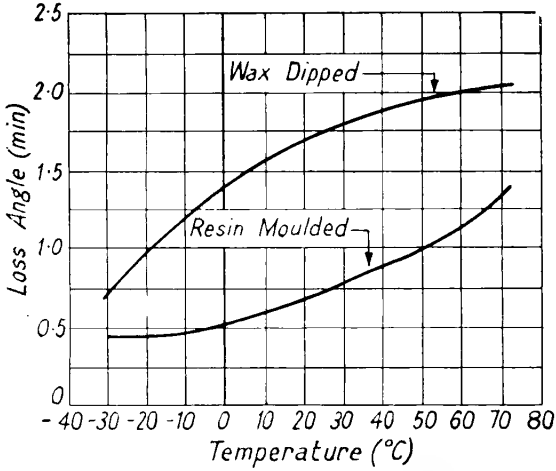

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FIG. 5.10. LOSS-ANGLE/TEMPERATURE CHARACTERISTICS OF 10,000-pF CAPACITORS AT 900 C/S

1 min of loss angle = 0·000291 × power factor

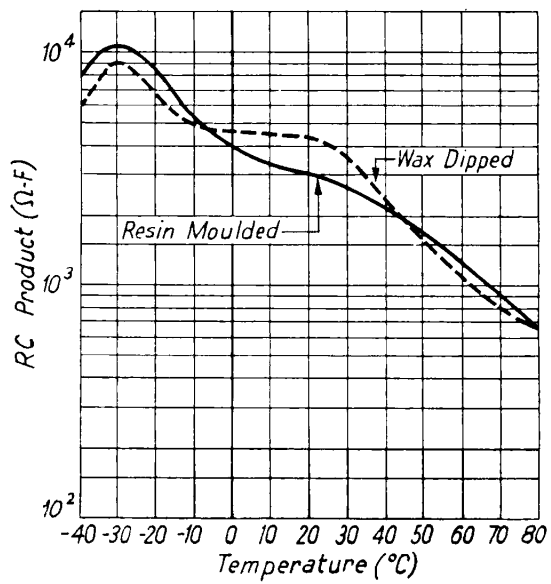

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FIG. 5.11. *RC*-PRODUCT/TEMPERATURE CHARACTERISTICS OF 10,000-pF CAPACITORS AT 300 V D.C. AFTER 1 MIN

referred to, and Fig. 5.12 shows the fall in insulation resistance for three types of covering.

Silvered-mica capacitors are not normally used as power capacitors as the current-carrying capacity of the silver film imposes a limit on the r.f. loading. An effect known as "scintillation"—random variations

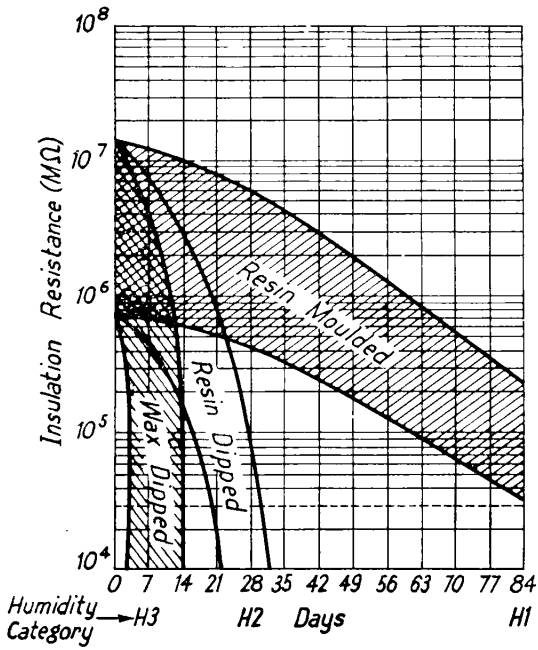

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FIG. 5.12. INSULATION-RESISTANCE/TIME CHARACTERISTICS OF CAPACITORS WITH THREE TYPES OF COVERING

Minimum insulation resistance, 20,000 MΩ (B.S. 2132)

in capacitance which cause frequency jumping—has been observed on silvered-mica capacitors (and also on silvered-ceramic types) when these capacitors are used in tuned circuits. This is due mainly to spasmodic discharges from the main silvered area to small islands of silvering isolated from the main area, or to minute cracks in the metallic layer, which result in "hot-spots" and sudden local expansion, when an r.f. voltage is applied. Because of the improvement in silvering techniques this effect should not occur with modern capacitors.

For experimental purposes, chemical silvering on mica is possible and one method will be described. The surface of the mica is cleaned in organic solvents, then the mica is washed in water. It is then activated

by immersion in 10 per cent stannous chloride solution, to which is added 15 per cent hydrochloric acid (in water). After washing in running water the mica is immersed in a mixture of 70 per cent formaldehyde solution, 30 per cent methyl alcohol. The solution is then drained off and the silvering is effected by immersion in the following solution (for 250 ml): one gramme of silver nitrate is dissolved in 50 ml distilled water, and ammonia is added until the brown precipitate first formed redissolves. The solution is then made up to 150 ml. To this, just before use, is added a solution of 6.0 g of Rochelle salt in 100 ml distilled water. Silvering takes about twenty minutes.

SYNTHETIC MICA

Attempts have been made, principally in Germany and America, to manufacture synthetic mica. It is technically possible to produce good-quality mica sheets, but the high cost of the plant necessary has prohibited further work. Synthetic mica can be made from a mixture of the following approximate proportions—

Aluminium oxide (Al_2O_3) .	11·5%
Magnesium oxide (MgO) .	32·7%
Sand (SiO_2) . . .	30·7%
Cryolite (K_2SiF_6) . .	25·1%

The materials, being only technically pure, are preheated in electrical furnaces to 900°C and then transferred to a special porcelain crucible in a main gas-fired furnace. The process of heating to melting point at 1,300°C and cooling to 900°C takes seven days, including three days allowed for crystallization by temperature gradient, cooling at approximately ten degrees per hour. The actual time of crystallization is five to six hours, but a safety factor of at least 500 per cent is allowed. The largest crystals produced are about 12 in. × 6 in., about 10 per cent being usable (i.e. greater than 1 in.^{2}). The use of a magnetic field to orient the crystals (mica being paramagnetic) might increase the useful yield to 20–30 per cent.

Synthetic mica is a phlogopite but, unlike natural micas, has no water in its composition. It is, therefore, stable nearly to its melting point of 1,300°C—the natural micas begin to give off water at about 400 to 500°C. It is more difficult to split than natural mica but has similar cleavage planes. Samples made so far, whilst of useful size, are superficially of poor quality compared with natural mica. The material is harder than natural muscovite, which in turn is harder than natural phlogopite. Flexibility is much the same and the characteristics favour punching. Power-factor measurements on early samples compare favourably with natural mica. The surface resistivity is of the order of ten to one hundred times that of natural mica, this being due

to the comparative purity. At high temperatures synthetic mica tends to absorb gas, rather than give it up; it is therefore singularly free from noise and is useful in making mica bridges for transmitting valves, for which purpose it was originally developed.*

MICA PAPER

Methods of manufacturing mica paper, in long sheets of even thickness, have been evolved in France and the U.S.A. Sheets are made from flake mica by a process somewhat resembling the making of paper. Muscovite and scrap mica are first shredded into flakes, then heated to a critical temperature and immersed in a solution of sodium bicarbonate, being then drained and saturated with hydrochloric or sulphuric acid. The mica is then washed and agitated and treated as paper pulp through a paper-making machine. Mica paper can be bonded with shellac, alkyd or silicone and is known as "mica mat". The power factor is higher than for natural mica and it is essential that the material be kept free from water. The raw mica mat can be wound round a 4 in. mandrel; it has a dielectric strength of approximately 400 V/mil. Its power factor is 3·5 per cent at 100°C and 3 per cent at 125°C, and it is therefore not normally used as a capacitor dielectric, but silicone-bonded glass-and-mica mat has a power factor of 0·023 at 25°C, 0·017 at 100°C and 0·018 at 125°C. It is made in the U.S.A. in thicknesses of the order of 0·0055 in. $\pm$ 0·0005.

INTEGRATED MICA

The method of manufacture of integrated mica makes use of the principle that the natural cohesive forces in thin freshly split flakes of mica are high enough to bond layers of flakes together to form a single sheet. No binder is used and the sheet possesses most of the electrical properties of the natural micas from which the flakes were originally split. All the four main types of mica can be integrated—muscovite, phlogopite, biotite and vermiculite. The mica is first split to a thickness of less than four microns by means of a disintegrator, which uses high-velocity water jets to split the mica pieces open. Water chambers are used to carry the disintegrated mica along and are arranged so that the thin flakes settle on to a belt which passes over a vacuum plate, keeping the flakes in place until the water is extracted. The resulting sheet is then dried. In order to overcome its fragility it is dipped in a solution containing 0·6 per cent silicone resin.

The electrical properties are uniform; the difference in permittivity between integrated mica and the material from which it is made is not more than 10 per cent—in most cases it is less than 5 per cent. The

* There has recently been a revival of interest in the production of synthetic mica in the U.S.A.

power factor depends to some extent on the impregnant, and for use in capacitors, impregnation with polystyrene or materials having low power factor results in a material with a power factor at 1 Mc/s of about 0·09 per cent. When made in the laboratory, with distilled water, a power factor as low as 0·03 per cent can be obtained. The dielectric strength of integrated mica averages about 400 V/mil for the unimpregnated material in a thickness of 0·01 in. The material is highly hygroscopic and the small percentage of silicone resin assists in preventing water absorption. It is possible to soften the material by subjecting it to saturated steam or heavily moistened air so that it can be rolled, dished or formed to make complicated parts. After the piece has been formed it is dried out and then impregnated.

MICA-DIELECTRIC TRANSMITTER CAPACITORS

The principal requirements for a transmitter capacitor are—

(1) High r.f. power-handling capacity.
(2) High d.c. rating.
(3) Low internal inductance.

The main uses of mica transmitter capacitors are in decoupling circuits where the r.f. is not much higher than 30 Mc/s or so. They are also useful in modulators. Mica power capacitors have advantages where high voltage rating and large capacitance values are required, because of their low power factor and high breakdown strength. The capacitor element usually consists of a clamped stack of selected mica sheets and tin-foil electrodes. All connections are soldered to ensure that high current ratings can be obtained. The stacks may then be mounted in a pot of porcelain and filled with wax to prevent the ingress of moisture. The capacitor is usually made up as a series combination, the arrangement depending on the working voltage required. The maximum capacitance and working voltage are therefore interdependent for each type. Typical characteristics for the pot type of transmitter capacitor are—

Max. kVA	*Max. R.M.S. Current* (*amp*)	*Max. Voltage* (*D.C. + A.C. peak*)
12	10	7,500
15	12 to 12·5	12,500
20	15 to 20	25,000
25	20	30,000

Capacitance values are normally obtainable up to about 0·7 μF, depending on the voltage and current ratings required. Sizes range from approximately 2 in. deep and $2\frac{1}{2}$ in. diameter, with terminals projecting 1 in. each end, up to approximately 10 in. deep, 6 in. diameter and $2\frac{3}{4}$ in. terminals. Typical pot-type capacitors are shown in Fig. 5.13.

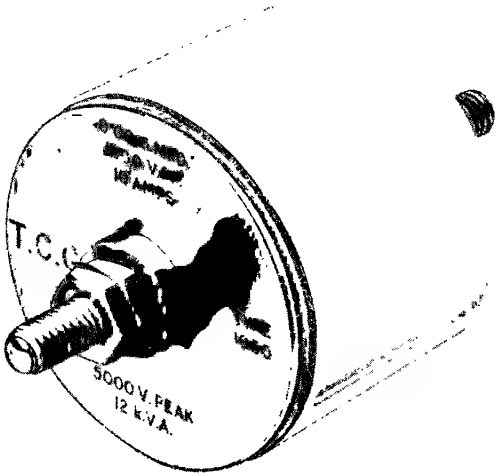

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FIG. 5.13. TYPICAL POT TYPE MICA TRANSMITTER CAPACITORS

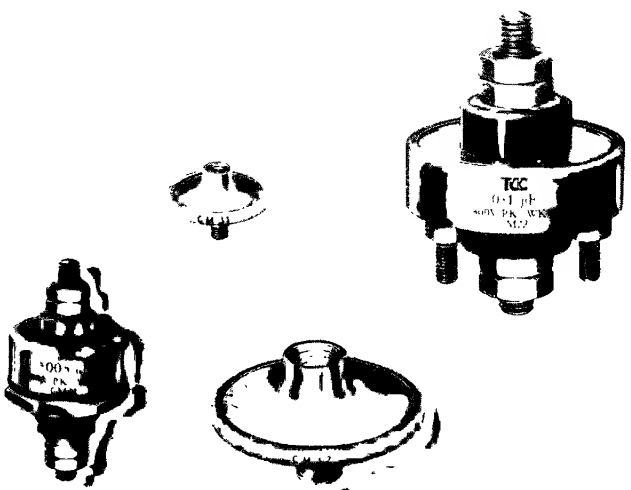

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FIG. 5.14. MICA DISC ASSEMBLY FOR TRANSMITTER CAPACITORS

Transmitter-type mica capacitors are also made in moulded-plastic rectangular cases for the lower voltages and in aluminium boxes with suitably insulated terminals for the higher voltages. Stacked-mica discs are also made which can be assembled in series or series-parallel for the capacitance values and voltage and current ratings required. The individual units are housed in circular plated brass containers (Fig. 5.14), with axially disposed terminations on opposite faces of the disc, one terminal being a threaded stud and the other a tapped hole. These assemblies lend themselves readily to air-blast cooling, thereby increasing the current rating.

Chapter 6

CERAMIC-, GLASS- AND GLAZE-DIELECTRIC CAPACITORS

Ceramic materials have been used for many years as electrical insulators. They are able to withstand severe working conditions because they are vitrified by firing at temperatures of the order of 1,200°C. Being completely inert they will withstand their rated working voltage indefinitely and retain their shape and physical characteristics under normal conditions. The following summary will be useful as an introduction to the various types of ceramic.*

Porcelain

The electrical types of porcelain are made from china clay (aluminium silicate), with quartz as filler and feldspar as flux. The proportions commonly used are two of china clay, one of quartz and one of feldspar. It has a comparatively poor power factor at high frequencies and a rather low volume resistivity at high temperatures. Its comparatively low thermal expansion and high positive change of capacitance with temperature are notable. It is mainly used for insulators at power frequencies. The technique of manufacturing intricate or large shapes in this material is well known. Glazing is advisable where it is necessary to minimize the deposition of dust.

Steatite

Steatite, or soapstone, in its natural (unfired) state is a coarse, massive or granular variety of talc, greasy to the touch. Chemically it is magnesium silicate. Fired at 800–1000°C it becomes very hard and strong. Materials produced from steatite or having steatite as their principal constituent are the most widely used of the low-loss ceramics. They combine reasonably low values of power factor, permittivity and temperature coefficient of capacitance with good mechanical strength. The thermal expansion is of the same order as that of a number of metallic alloys, thus making them useful for sealing techniques. The resistivity at high temperatures is better than that of porcelain. These properties make the steatite class of ceramic a general-purpose high-frequency insulator, and it is widely used in components such as variable capacitors, coil formers, valve-holders and bases and for general structural insulation.

* The first ten items in the summary have been extracted from a document written by the staff of the British Institution of Radio Engineers.

Forsterite

This material chemically is another magnesium silicate but of a different composition from steatite. Its outstanding properties relative to the latter are a very low power factor and a high thermal expansion. It is intended for applications where the lowest possible dielectric loss is important; also where vacuum-tight joints have to be made with metal parts, as for example in electronic tubes. Its suitability for the latter application results from the ability to ensure that it has a coefficient of linear expansion which closely matches that of some nickel-iron alloys. It is suitable for high-temperature metallizing techniques. The commercial grades have been developed with particular attention to the attainment of high physical and chemical stability and negligible porosity.

Cordierite

This mineral is a magnesium aluminium silicate with the chemical composition $2MgO.2Al_2O_3.5SiO_2$. Although this substance has never been found in any sizeable natural deposit, cordierite crystals can be developed in a ceramic body of the composition talc 39·6 per cent, clay (pure kaolin) 47 per cent and alumina 13·4 per cent. Variants of this composition suitably processed provide a ceramic body consisting in some cases of 60 per cent cordierite crystals.

Such a ceramic has the outstanding property of a very low thermal expansion, but its power factor is relatively high, being of the same order as that of porcelain. In these respects it will be seen to contrast with forsterite. The low thermal expansion ensures very good resistance to thermal shock; this virtue leads to its usage outside the sphere of high-frequency applications—in electrical heater plates, as cores for electrical resistors, for resistance wire supports and other similar purposes in various types of equipment. The mechanical strength of this class of material is not notable, but with due attention to shape design in relation to the intended use it is adequate.

In the high-frequency field advantage may be taken of its low thermal expansion by use, for example, as formers of coils which are desired to have a minimum change of inductance with temperature. In by no means all such applications could its relatively high power factor be regarded as a disqualifying feature.

Rutile

This mineral is a dioxide of titanium which crystallizes as reddish-brown prismatic crystals in the tetragonal system. It is found in igneous and metamorphic rocks and is a source of titanium. The material has the notable electrical characteristics of a high permittivity

and, unlike most other materials, a high negative temperature coefficient of capacitance. These properties are accompanied by a low power factor and good mechanical characteristics.

It is chiefly used as the dielectric of capacitors, an application where high permittivity combined with low power factor is an obvious advantage. The high negative temperature coefficient of capacitance of such capacitors becomes a virtue when appropriately utilized to compensate the positive coefficient of other elements in a particular circuit application.

It is of passing interest to note that rutile bodies often show firing shrinkages as high as 25 per cent or even greater.

Magnesium Titanate

A number of special ceramic bodies are made by using 60–90 per cent rutile with one or more of the oxides of magnesium, barium, beryllium lead and zirconium. Most of these bodies are characterized by a very low power factor; magnesium titanate is a typical example. In a specific case the power factor may be lower than that of a rutile body, and this feature combined with the low temperature coefficient of capacitance which also characterizes magnesium titanate makes it attractive for high-frequency applications.

It is commonly used as the dielectric of capacitors where low loss or high power-handling capacity is of prime importance.

Barium Titanate

A particular variant can be made to have a combination of very low power factor, low temperature coefficient of capacitance and moderately high permittivity—characteristics which are somewhat similar to those of magnesium titanate and which lead to this variant having a similar field of application.

Other variants have been evolved to provide a remarkably high value of permittivity, thus making possible the construction of relatively high-value capacitors in small dimensions while still retaining a tolerable dielectric strength. The power factor of this variant is high but is not a disadvantage in the uses, such as by-pass capacitors, to which this material is put.

In general, barium titanate does not claim special attention in the constructional aspects of equipment engineering. Its unique ferroelectric and piezoelectric properties, however, attract a wide interest.

Alumina

This material is the trioxide of aluminium and occurs as the mineral corundum. Ceramics having a high alumina content are notable for their ability to withstand very high temperatures up to about 1750°C;

consequently they are commonly used as the electrode supports in electronic valves, as sparking-plug cores and in similar applications.

Recrystallized or sintered alumina retains its ability to withstand high temperatures and also has notably high mechanical strength (of the order of twice that of porcelain). The thermal conductivity of sintered alumina is outstanding, being about twenty times that of porcelain and more nearly comparable with that of steel. This class of material has a reasonably low power factor at 1 Mc/s and there is evidence that it remains of this order at frequencies of about 3 Gc/s.

Pyrophyllite

This clay mineral is a silicate of aluminium with chemically combined water. It occurs in metamorphic rocks and often resembles talc. Ceramic bodies can be made by firing this material without entailing significant shrinkage such as is encountered in other classes of ceramics. Shrinkage rates are about 3 to 4 per cent. Pyrophyllite bodies in the unfired state are machinable with conventional tools. These two features make it attractive for experimental and prototype use.

The fired bodies have a mechanical strength comparable with that of porcelain. The power factor of certain mixes based on this material is of the order of 2×10^{-3} and the permittivity about 5.

Zircon

During the past few years much experimental work has been done on ceramic bodies having zirconium silicate as their major constituent. The principal object has been to evolve a low-loss ceramic material which could be fabricated by conventional whiteware forming methods and fired in large commercial tunnel kilns without excessive wastage of the finished product. The firing temperature range of steatite and other types of electrical ceramics is relatively restricted, therefore dictating the use of special small kilns and precise control of the firing process. The zircon bodies allow wider firing ranges; consequently they appear to offer an advantage in production costs.

The permittivity of some typical zirconium compounds is 8 to 10 and different variants have power factors ranging from 2×10^{-4} to 8×10^{-3}. The coefficient of liner expansion is of the order of 3·0 to 6·0, and resistance to thermal shock is greater than that of the majority of electrical ceramics. Other mechanical characteristics are comparable with those of steatite.

Pyrophillite, or Wonderstone

"Pyrophillite" is a ceramic-like material which occurs naturally in South Africa. It is a sedimentary fine-grained compact rock of metamorphosed clay, derived from volcanic ash. Its main value lies in that

it can be readily machined, sawn, cut, filed, etc., into any required shape, in addition to possessing good electrical characteristics, mechanical properties and corrosion resistance. The material is composed largely of silica and alumina, the constitution being as follows.

	%		%
Silica (SiO_2)	56·0	Lime (CaO)	0·27
Alumina (Al_2O_3) . . .	33·3	Magnesia (MgO) . . .	0·22
Ferric oxide (Fe_2O_3) . .	0·77	Loss on ignition . . .	7·04
Titanium oxide (TiO_2) . .	2·4		

It can be fired at about 1,100°C with little change in dimensions. It commences fusion as a refractory material at 1,630°C, collapsing at 1,650°C, the precise temperatures being governed by the amount of impurities present. The permittivity at 1 Mc/s is 8·0 in the natural state and 4·8 when fired; the power factor at 1 Mc/s is 0·1. Its main disadvantage is that it exhibits bedding planes which, unless the material is carefully selected, affect the structural strength of any article made. It is also very hygroscopic, even after firing.

Bentonite

Bentonite clay, which is chemically similar to mica, is found in many parts of the world. It is possible to make dielectric film out of bentonite-clay derivatives. The advantages of such a film are high permittivity,

TABLE 6.1. CHARACTERISTICS OF BENTONITE CAST FILM
(*Aircraft-Marine Products Co.*)

Thickness: 0·5 mil ± 0·1 mil
Temperature coefficient of capacitance (over temperature range −55° to +125°C: 0·015 per cent deg C
Permittivity over the temperature range −55° to +125°C: 4·3
Power factor at 25°C: 1 kc/s = 0·0023
1 Mc/s = 0·0017
Insulation resistance: 10^{15} Ω-cm
Dielectric strength (from −55° to −175°C):
1-mil sheet = 5,000 V/mil
2-mil sheets = 4,000 V/mil
Chemical stability: stable to 250°C
Corona resistance: good
Physical properties: insoluble, inelastic and incompressible

low dielectric absorption, and mechanical and electrical stability over a wide temperature range.

Dielectric strengths of such a film that can be made in the United States are consistently obtainable of the order of 10 kV/mil when 1-mil samples are measured between ball electrodes under oil. This test voltage is a peak voltage at 60 c/s.

The material is brittle and incompressible, and behaves much like a

piece of glass of comparable thickness. The base film will show a degradation in power factor when exposed to moisture. In the United States, a bentonite cast film (Amplifilm*) is manufactured with the characteristics shown in Table 6.1.

The present field of application is for high-voltage pulse capacitors (used sometimes as part of pulse-forming networks) and high-voltage filter capacitors for radar modulators and indicators. The characteristics for such capacitors are shown in Table 6.2.

These capacitors are constructed by the use of heavy copper electrodes, stacked with dielectric film and then banded together under

TABLE 6.2. CHARACTERISTICS OF HIGH-VOLTAGE FILM CAPACITORS
(*Aircraft-Marine Products Co.*)

Capacitance range: 25 to 100,000 pF
Capacitance tolerance: ±5 per cent
Dissipation factor (25°C and 60 c/s): 0·35 per cent average, 0·5 per cent maximum
Voltage rating (−25° to +125°C): 0 to 9,000 V pulse, 0 to 11,500 V direct current
RC product: at 25°C = 100,000 Ω-F
at 125°C = 50 Ω-F
Capacitance variation with frequency 1 kc/s to 10,000 kc/s: ±1 per cent
Capacitance variation with temperature −55 to 125°C: ±3 per cent

high temperature and pressure with a thermoplastic resin. When they are used in applications other than oil-filled, as when encased in an encapsulate, care must be taken to avoid ionization (corona).

THERMAL SHOCK IN CERAMICS

Thermal shock has always been a problem of ceramics. In ceramic dielectrics it is dependent principally upon linear thermal expansion, the lower the thermal expansion the higher being the thermal shock resistance. Fig. 6.1 shows the effect of linear thermal expansion on thermal shock resistance of some dielectrics. Steatite has the highest linear thermal expansion, and specimens $\frac{1}{2}$ in. in diameter by 10 in. long fail when quenched into water at room temperature from between 150° and 165°C. The other dielectric insulators shown have lower thermal expansion and resist failure by thermal shock from higher temperatures.

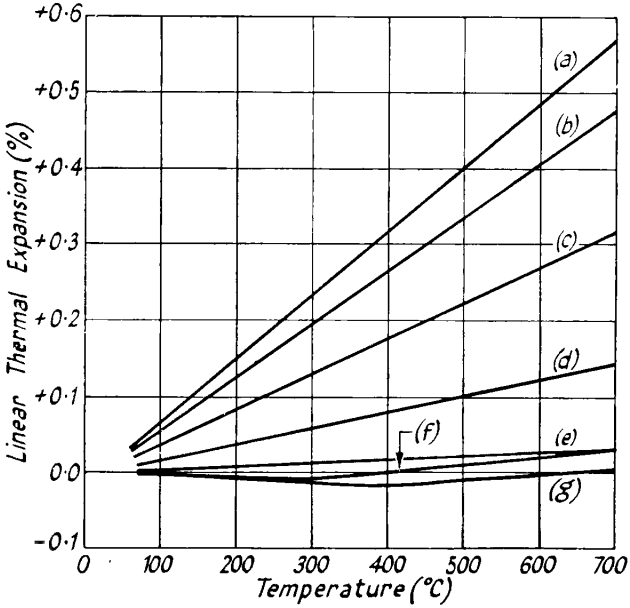
THE STRUCTURE OF CERAMICS

The structure of high-permittivity ceramics has been excellently described by Fielding Brown†, substantially as follows.

A polycrystalline material, such as that normally used in disc-type high-permittivity capacitors, consists of numerous single crystals.

* Registered trade mark of Aircraft-Marine Products Co.
† *Trans. Inst. Radio Engrs.* **CP-6** (Dec., 1959), 238.

These are oriented at random, and recrystallize in the sintering process in such a way as to fit together compactly. In a typical barium titanate ceramic, the crystallites may be of the order of 2–10 μm in diameter, although finer particle sizes are possible, and the porosity (reduction in



E. J. Smoke

FIG. 6.1. EFFECT OF LINEAR THERMAL EXPANSION ON THERMAL-SHOCK RESISTANCE OF VARIOUS DIELECTRICS

(*a*) Steatite, 150°–165°C
(*b*) Alumina, 200°–230°C
(*c*) Zircon, 230°–260°C
(*d*) Cordierite, 290°–315°C
(*e*) Fused silica
(*f*) Lithia, 600° 650°C
(*g*) Luthia, above 1,200 C

The temperatures quoted are those at which thermal-shock failure occurs

bulk density from that of a single crystal) may range from nearly 0 to 5 or 6 per cent. Judging by the complexity of domain patterns in ceramics, the sintering process must leave the crystallites in a state of considerable strain. This is further evidenced by the fact that mechanical separation of a crystallite from its surrounding matrix causes domain patterns on its surface to become more regular.

As has been shown by Merz, hydrostatic pressure lowers the Curie temperature of single-crystal barium titanate. The case of polycrystalline ceramics has been considered by Jonker, who points out

that widely distributed internal stresses may have the effect of broadening the peak of permittivity near the Curie point. This is particularly interesting for the design of ceramic dielectrics since it indicates a method for overcoming at least a part of the excessive temperature variation of permittivity in this temperature region. In fine-grained ceramics where the ratio of crystallite surface area to volume is relatively large the effect can be expected to be more pronounced.

Structure is also important when considering the possible effects of internal depolarizing fields. At the boundary of a uniformly polarized domain, the bound polarization charges will, in general, not be neutralized completely by polarization of the surrounding matrix. In the absense of conductivity, very complex internal fields may thus exist and influence the properties. Such fields may play a role even when conductivity is present if dynamic behaviour is considered. Unfortunately, the detailed picture of microscopic depolarizing fields is at present too involved to consider quantitatively, but has been cited by Kniephamp and Heywang as a possible explanation of the effect of fine particle size on dielectric properties.

The grain boundaries themselves may also influence electrical behaviour. They may be thought to consist of regions of lattice disorder a few lattice constants wide in which the crystallographic orientation changes from one crystallite to another. This disorder undoubtedly alters the local field in the boundary region and affects the characteristic pattern of domains. Domain walls, none the less, have been observed to extend continuously across the grain boundaries.

Grain boundaries may also affect semiconducting properties. It has been postulated that the boundaries, being paths of rapid ionic diffusion, are reoxidized more quickly and completely on cooling from the slightly reduced state at the firing temperature of the ceramic to room temperature. Thus, electronic inhomogeneity results and space-charge polarization effects arise. It is further suggested that grain boundaries may play a role in transmitting lattice vacancies in barium titanate under operating fields at temperatures above 200°C. The vacancies, in turn, contribute to the ultimate breakdown of the material by acting as donor sites for electronic conductivity. One can look, therefore, for an effect of second phases at boundaries in influencing resistivity and life of ceramics.

For all the above reasons, the exact nature of polycrystalline structure is of great importance in determining operating performance of high-permittivity ceramics. Since our knowledge of the facts is very imperfect, resting often on empirical findings and on hypotheses, it can be expected that much technical progress still lies ahead as sound fundamental information continues to accumulate.

CERAMIC-DIELECTRIC CAPACITORS

Low-loss Low-permittivity Ceramic Capacitors

As the materials are naturally occurring minerals they contain impurities. Therefore, after they have been finely ground, intimately mixed and compressed into tough but suitable shapes they are "calcined" at a temperature below the fluxing or melting point, which is sufficient to oxidize any organic matter and reduce to oxides any carbonates, chlorides or sulphates present. The resultant mass or body is

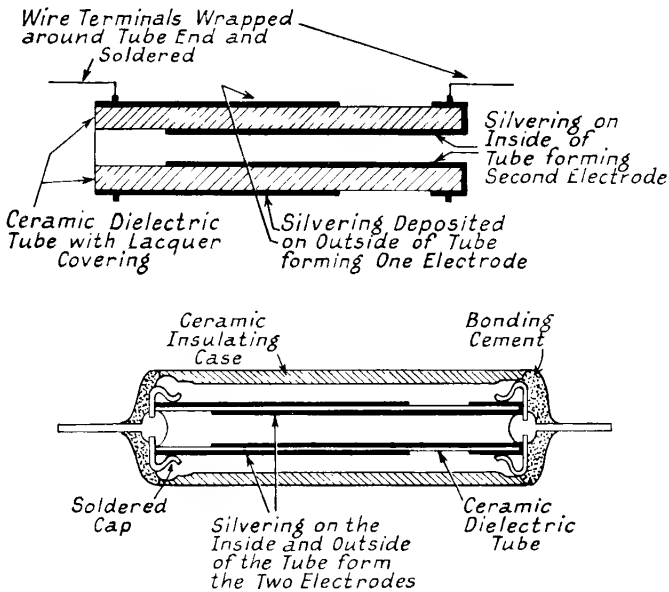

Wire Terminals Wrapped around Tube End and Soldered
Silvering on Inside of Tube forming Second Electrode
Ceramic Dielectric Tube with Lacquer Covering
Silvering Deposited on Outside of Tube forming One Electrode
Ceramic Insulating Case
Bonding Cement
Soldered Cap
Silvering on the Inside and Outside of the Tube form the Two Electrodes
Ceramic Dielectric Tube

Fig. 6.2. Construction of Insulated and Uninsulated Ceramic Capacitors

then reground. The calcined finely ground "body" is then mixed with water and binding or emollient matter (such as gum or oil) and mechanically reduced to a smooth stiff paste from which pressure mouldings and extrusions into capacitor bodies can be made. A carefully controlled drying sequence follows until ultimately the capacitors are fired in a controlled atmosphere (generally oxidizing) at temperatures between 1,200 and 1,400°C until vitrification occurs, ensuring non-porosity.

Capacitors are usually made in tubular shape but can also be made as flat plates or strips. The construction of typical insulated and uninsulated tubular capacitors is shown in Fig. 6.2.

Low-loss capacitors are usually made from steatite (more commonly known as "talc") which has a permittivity of approximately 8. This is fluxed with one of the feldspars, or preferably an alkali-free flux such as witherite ($BaCo_3$).

The ceramic dielectric material is in the form of a tube, and the capacitor is formed by metallizing part of the internal and external surface of the tube. This is usually done by brushing on a silvering solution and firing, or sometimes by dipping the tube (suitably masked) into a silvering solution. Firing to reduce the silver solution to metal is usually carried out at about 700 to 800°C.

If the silvering process is not done carefully, scintillation (p. 109) can occur, and all brushing, cleaning, etc., is therefore carefully controlled throughout the manufacture. Poor silvering may also affect the temperature coefficient.

The capacitance of a tubular capacitor can be calculated from the formula

$$C = \frac{0{\cdot}0241 l\varepsilon}{\log_{10}(D/d)} \times 10^{-6} \text{ microfarads}$$

where l = overlapping part of the metallizing in millimetres,

D = outer diameter of the tube in millimetres,

d = inner diameter of the tube in millimetres,

ε = permittivity of the ceramic material.

It can be seen from this formula that the capacitance of a tubular capacitor is independent of the diameter of the tube, provided the ratio between the inner and outer diameters remains the same; the capacitance depends only on tube length and length of silvering. In contrast with the capacitance, the breakdown voltage of a tubular capacitor varies with the wall thickness of the tube. The general characteristics of a steatite-base capacitor are given below.

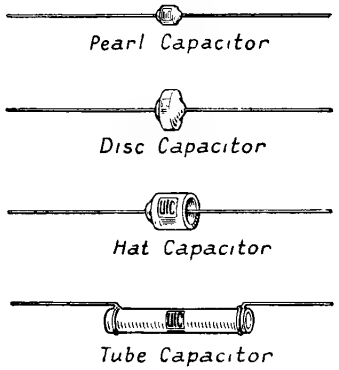
ε at 1 Mc/s	5 to 7
tan δ	0·001
Temperature coefficient	Varies from + 100 to + 120 ppm/°C
Frequency range	Approximately 100 c/s to 200 Mc/s
Maximum temperature of operation	Approximately 150 °C (usually limited by covering and solder connections)
Minimum temperature of operation	No intrinsic limit
Breakdown voltage	Approximately 500 V (depending on size)

In addition to tubular, rectangular and stand-off types, these capacitors are made in other shapes—disc, hat, etc. as shown in Fig. 6.3.

Medium-permittivity Ceramic Capacitors

The medium-permittivity dielectrics now in use are all based on titania (titanium dioxide, TiO_2) or its derivatives, the alkaline-earth titanates ($M.TiO_3$). Titania is very widely distributed, occurring in a mineral form as rutile, anatase and, less frequently, as brookite: in combination it occurs chiefly as ilmenite and perovskite. Its refining, however, is a matter of considerable difficulty.

The general physical properties of all the resulting dielectrics are



U.I.C., Ltd.

Fig. 6.3. Ceramic-dielectric Capacitor Shapes

very similar, and their method of preparation follows the ordinary ceramic methods previously described, in oxidizing atmospheres. The processing is, however, more difficult, owing to the danger of partial reduction and the need for accurate temperature control.

The materials are extremely hard, refractory and chemically inert. Electrically, they are fairly good insulators, but the breakdown voltage is low compared to that of mica, and conduction becomes serious at temperatures of 150°C or more. Their main use is in capacitors.

The exceptionally high permittivity of titania in all its three mineral forms was first noticed by Schmidt in 1902. For rutile he found a permittivity of 170 parallel to the crystal axis and 80 perpendicular to it; values were low for anatase, which also belongs to the tetragonal crystal system; for brookite, which is rhombohedral, he gave a permittivity of 80.

His values were confirmed in 1934 by Euckon and Buchner, who

studied the temperature dependence of the permittivity, using sections of large single crystals, again of mineral origin. They concluded that for rutile the permittivity parallel to the axis passes through a minimum near room temperature; perpendicular to the axis, the minimum occurs at — 100°C. It is not certain that this would occur in pure materials (as opposed to those of mineral origin). For anatase they found that the permittivity along the axis increases steadily with the temperature from — 100 to + 100°C. No observations were made on brookite, or on anatase perpendicular to the axis. Since these measurements were made on mineral samples, the part played by impurities remains uncertain. In 1935, French workers, using highly compressed masses of chemically pure titania, confirmed the very high values observed by Schmidt, and by Eucken and Buchner (allowing for the incomplete space-filling of the compressed mass, and for the random orientation of the particles). The high permittivity of titania was thus established, and shortly afterwards it was marketed in a number of forms.

The main characteristics of this type of material when made into capacitors differ from other materials as follows.

There is a change of capacitance with temperature of the order of — 800 ppm/°C for TiO_2. The power factor is usually less than 0·0003 at radio frequencies. The high permittivity persists up to the highest radio frequencies. The loss, with titania only, increases at lower frequencies, being of the order of one or two per cent at 1 kc/s and becoming very large at a few hundred cycles per second, but with suitable additions the loss can be made much smaller.

The addition of increasing amounts of barium oxide first lowers the permittivity, then raises it, at the same time changing the sign of the temperature coefficient. Low-loss and linear characteristics persist until the proportions of the mix are almost equimolecular, so that, up to these proportions, barium-titanium oxide behaves as a normal dielectric of very high permittivity, showing no evidence of hysteresis. Titania-calcium oxide mixtures behave similarly, and useful dielectrics can be made with compositions approximating to calcium titanate (permittivity, about 150; temperature coefficient, 1,200 ppm/°C). Magnesia-titania mixtures give lower permittivities, that for compositions approximating to magnesium titanate being 14 to 16, with a positive temperature coefficient.

Using suitable mixtures of titania and the alkaline earths already mentioned the temperature coefficient can be controlled, giving small capacitance values for positive temperatures, through zero, to high values for temperatures below zero, and these dielectrics are used mainly in temperature-compensating capacitors for communication receivers, etc.

For capacitors with medium permittivities (70 to 100) the shape of

the capacitance/temperature graph is shown in the typical curve of Fig. 6.4.

High-permittivity Ceramic Capacitors

The main advantage of this type of capacitor is the possibility of obtaining a large capacitance in a small volume. Permittivities of 1,000 to 5,000, or more, are realizable, but with certain limitations.

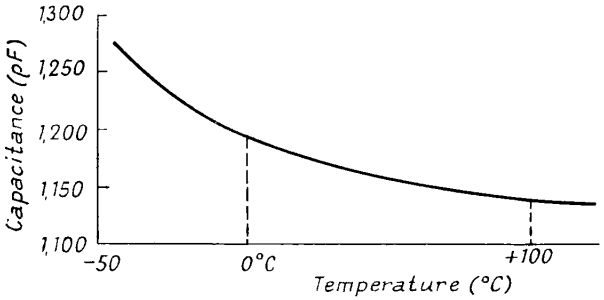


Fig. 6.4. Capacitance/Temperature Curve for Medium-permittivity Ceramic Capacitors

The methods of manufacture follow principles similar to those already described. For permittivities of this order, barium titanate (pure or with the barium partly replaced by other metals) is used. This material

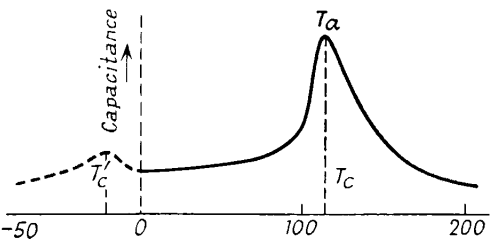


Fig. 6.5. Permittivity/Temperature Curve for Typical High-Permittivity Ceramic Capacitor

is exceptional in showing a Curie point and associated ferro-electric properties. If ultra-high values of permittivity are required free from hysteresis, they can only be obtained reliably by working above the Curie point. They will have a large negative temperature coefficient but their total range of usefulness may well be considerable. By choosing compositions which give Curie points at very low temperatures it is possible to produce reliable materials with usefully large permittivities, giving a reasonably linear change with temperature over normal operating temperatures, and relatively low loss.

The equimolecular mixture of barium oxide and titania, having the composition $BaTiO_3$ (barium titanate), has entirely different properties from the medium-permittivity titania and related dielectrics. The permittivity varies with temperature in the manner shown in Fig. 6.5. There is a very large peak at a certain temperature T_a (around 110 to 120°C) at which a value of at least 9,000 may be attained. Above this, the permittivity falls according to the Curie law

$$\varepsilon = \frac{a}{T - T_c}$$

where a = constant,
T = actual temperature in degrees Centigrade,
T_c = Curie point temperature.

T_a differs only slightly from T_c. Below T_a, the permittivity drops abruptly to a relatively low value, usually of the order of 1,000 to 1,500, at which it remains constant down to a second Curie point T_c' at approximately 0°C and then falls off.

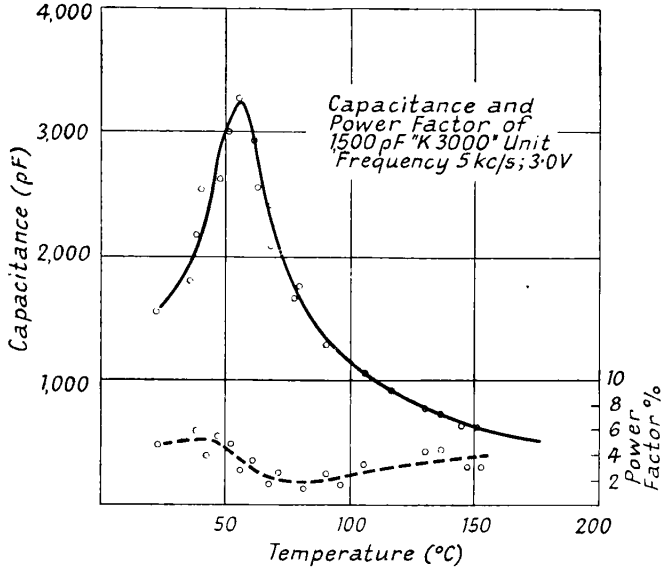
The most important electrical change is that hysteresis (*see* p. 131), with greatly increased loss in strong fields, sets in below T_c but is absent above it. Hence, below this the permittivity and power factor can only be defined for vanishing field-strength.

The temperature T_c' previously referred to is often termed the lower Curie point. It corresponds to a second change of crystal structure; it does not correspond to any very marked changes in the electrical properties, and in particular, hysteresis is unaffected.

The Curie temperature of barium titanate is approximately 120°C. It is lowered if some of the barium is replaced by strontium; for 70:30 (Ba:Sr) titanate it is at 0°C, and for a 40:60 mixture it is at — 120°C, and within this range the Curie point temperature falls linearly with the composition. If, instead of replacing barium by strontium, the proportion of titania is reduced in the $BaOTiO_2$ mixture, the Curie point is lowered and may even be split. Other materials, such as calcium mixes, can also be added to lower the Curie point. The substitution of lead for some of the barium raises the Curie point.

At the Curie point, a number of important physical changes occur. The crystal lattice, cubic at high temperatures, passes to a tetragonal form, one edge of the elementary cube being extended and the other two contracted, while the whole structure undergoes a slight shear. The precise ionic displacements involved are not yet known and considerable research is being done on this problem.

The effect of these changes is reflected in the final capacitor, as shown in the typical capacitance/temperature curves for commercial capacitors of values 1,500 pF ($\varepsilon = 3{,}000$) and 1,000 pF ($\varepsilon = 1{,}250$) in Fig. 6.6.



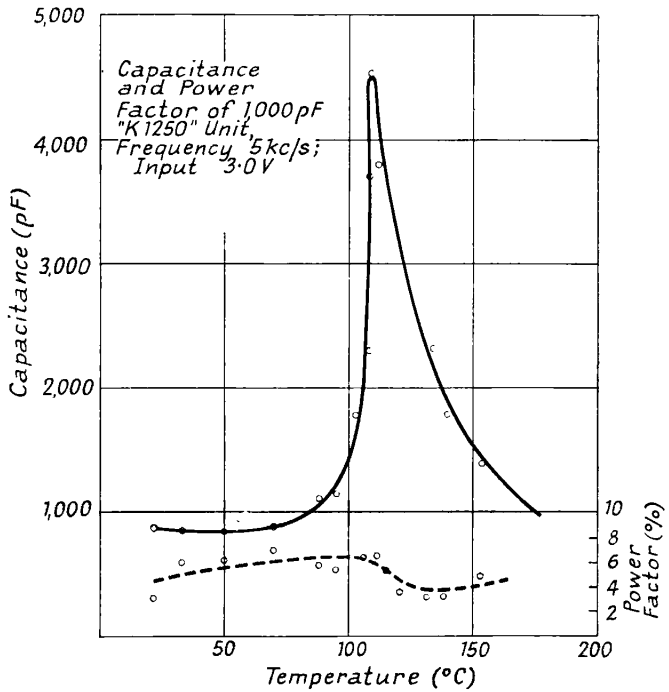
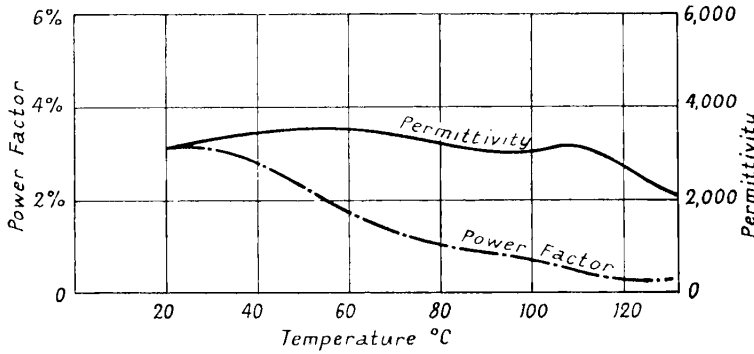


FIG. 6.6. CAPACITANCE/TEMPERATURE AND POWER-FACTOR/TEMPERATURE CURVES FOR $\varepsilon = 3{,}000$ AND $\varepsilon = 1{,}250$ CERAMIC CAPACITORS

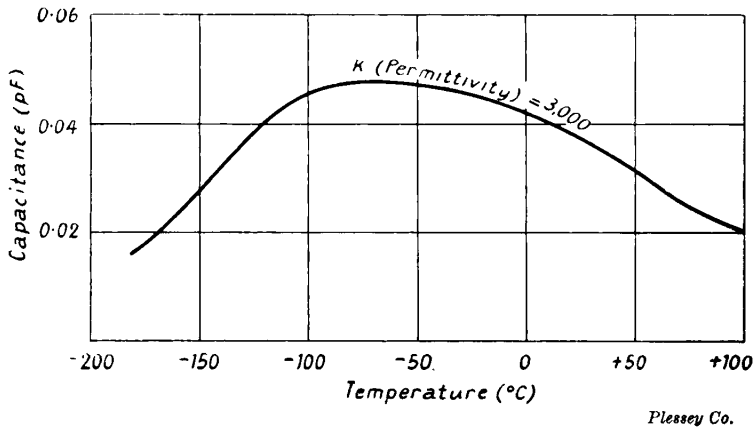
The peak of the curve can be moved along the temperature axis by varying the mix, and many attempts have been made to flatten the curve by adding various materials, chiefly to the barium-strontium



Steatite and Porcelain Products, Ltd.

FIG. 6.7. PERMITTIVITY/TEMPERATURE AND POWER FACTOR/TEMPERATURE CURVES FOR TYPICAL HIGH-PERMITTIVITY DIELECTRIC

series of titanates. The effects of these additions vary. For instance, magnesium lowers the power factor, broadens the permittivity peak and lowers the temperature at which it occurs. Zirconium



Plessey Co.

FIG. 6.8. CAPACITANCE/TEMPERATURE CURVE FOR "K" (or ε) = 3,000 CAPACITOR

behaves similarly but it does not affect the power factor. Tin has less broadening effect than zirconium. Lead shifts the peak to higher temperatures.

Constant endeavours are being made in the U.K. and the U.S.A. to

achieve a reasonably flat curve by combinations of additives of this type. The shape of these curves indicates that when specifying a required capacitance it is best to specify a minimum capacitance, particularly for decoupling and other purposes, so that temperature variations will increase the capacitance and not reduce it.

A typical curve for a good modern high-permittivity capacitor is shown in Fig. 6.7, from which it can be seen that over the range 20 to 100°C the curve is sensibly flat.

Over a wider temperature range, capacitors have been made, with

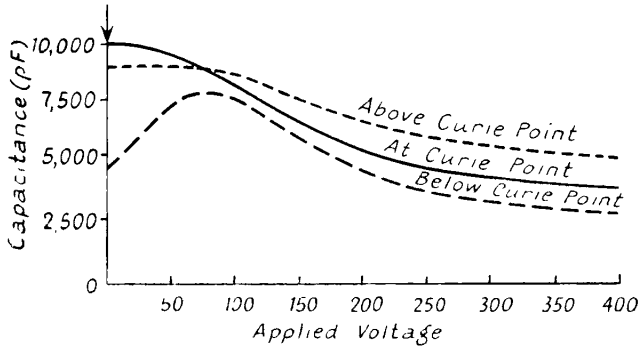


FIG. 6.9. VARIATION OF CAPACITANCE WITH APPLIED VOLTAGE FOR HIGH-PERMITTIVITY CAPACITOR

$\varepsilon = 3{,}000$, which have the capacitance/temperature characteristics shown in Fig. 6.8.

The effect of a large d.c. bias on the capacitor is to reduce its capacitance and to flatten the capacitance/temperature curve. The amount is dependent on whether the capacitor is operated above, below or at its Curie point. A typical graph of the effect of d.c. bias on capacitance is shown in Fig. 6.9.

The variation of capacitance with temperature at differing applied voltages takes the form of the curves shown in Fig. 6.10.

Hysteresis Losses, etc., in High-permittivity Capacitors

High-permittivity capacitors are ferro-electric at room temperatures, i.e., the charge and voltage are not linearly related, but a hysteresis loop is described during a charging cycle, resembling the magnetization loop for iron.

The ferro-electric properties place severe limits on the use of such materials as dielectrics. These properties can be most clearly understood from Fig. 6.11, which is drawn for a general case.

Under large voltage swings, the curve $ABCD$ is described in the sense shown. The energy dissipated per cycle is equal to

$$\int V\, dQ$$

where V = applied voltage, and

Q = charge.

that is, to the area enclosed by the loop. Hence, with large alternating voltages, the unit is highly dissipative and energy is lost. Moreover,

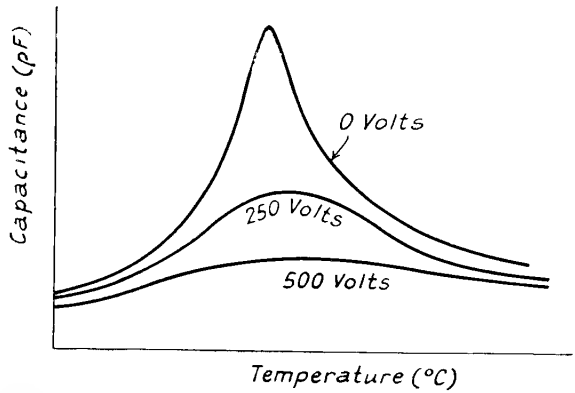


FIG. 6.10. VARIATION OF CAPACITANCE WITH TEMPERATURE AT DIFFERENT APPLIED VOLTAGES FOR HIGH-PERMITTIVITY CAPACITOR

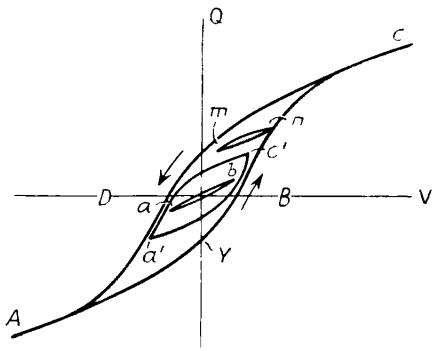


FIG. 6.11. TYPICAL HYSTERESIS LOOPS FOR A FERRO-ELECTRIC SUBSTANCE

it produces considerable harmonic distortion. For small alternating voltages, the capacitor is "normal," although the power factor is poor, possibly about 1 per cent. Operation is then along the narrow loop *ab* as in the diagram. Further increase of the voltage would make this

curve tend to cross the boundary of the hysteresis loop, which is physically impossible, and a path such as $a'c'$ must be described. Hence the loss increases severely at this stage. It will be seen from the diagram that the polarization does not vanish with the field: a certain remanent polarization Y still exists. This does not produce an external field under static conditions, as it is neutralized by surface charges, but in applications which require similarity in the behaviour of two elements, this value plays an important part. Under large fields, the behaviour of a high-permittivity capacitor has no counterpart with that of ordinary capacitors and for other than small voltages it becomes exceedingly complex. The behaviour may be summarized as follows.

(*a*) *Superposed a.c. and d.c. fields.* So long as the d.c. field is not large enough to saturate the element, and the alternating voltage is less than the coercive field, it is clear that during the first charging half-cycle, a path such as *mn* in the diagram will be obtained. The limiting alternating voltage and the incremental capacitance and power factor are not very much affected by the d.c. field, although the capacitance falls slowly as the bias increases.

For larger alternating voltages, a hysteresis loop must be described, unless the bias is so large that the total field never falls below the saturating voltage. For such fields, the only effect of the d.c. bias is to shift the entire figure along the voltage axis.

(*b*) *Superposed a.c. fields of different frequencies.* For small fields, the element acts as a normal capacitor. If a high-frequency field of small amplitude is imposed on a low-frequency field of much larger amplitude, the normal hysteresis loop is described. Using a cathode-ray-tube display, the varying speed of the light spot causes intensity modulation of the trace, when the two frequencies are simply related, as shown in Fig. 6.12 (*a*).

If, however, the amplitude or the frequency of the high-frequency component is increased, so that, during part of its cycle, dV/dt changes sign, this is no longer the case, for the hysteresis loop can only be described in one sense. Consequently, a path such as Fig. 6.12 (*b*) appears on the c.r.t. display.

These simple examples show the complexity of the effects which may arise in non-linear capacitors.

The quantities described above are also temperature-sensitive: the hysteresis loop becomes narrower with rise of temperature, eventually vanishing at the Curie point. Above this point the substance behaves almost as a normal dielectric with a very high permittivity, the permittivity falling with further increase of temperature. Simple mixes

with a high barium content cannot be used in this state, owing to the large conduction loss, but modern commercial materials, with no marked Curie points, give a much better performance in respect of power factor and conductivity at high temperatures.

It will be seen, therefore, that where high d.c. bias or large a.c. fields

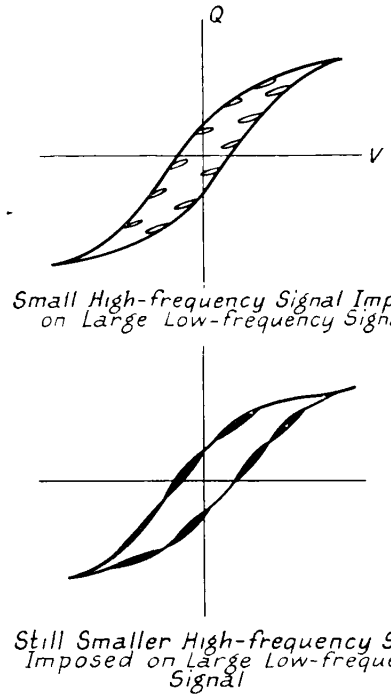

Q
V
(a) Small High-frequency Signal Imposed on Large Low-frequency Signal
(b) Still Smaller High-frequency Signal Imposed on Large Low-frequency Signal

FIG. 6.12. HYSTERESIS LOOPS FOR HIGH-PERMITTIVITY CAPACITORS WITH SUPERPOSED A.C. FIELDS

are involved, or where wide temperature ranges are required, great care should be taken in the use of high-permittivity capacitors.

"Creep" in High-permittivity Capacitors

A phenomenon which has recently become associated with high-permittivity capacitors is that known as "creep." This is a change in internal resistance with time, which becomes marked at high temperatures, i.e. over 100°C. It is a separate effect from normal high leakage currents and is being studied. The increase of leakage current over 100°C may be quite serious.

Types of High-permittivity Capacitors

Most high-permittivity capacitors are tubular types, made by methods similar to those described for the manufacture of low-loss ceramic tubular types. They are used mainly as by-pass or decoupling capacitors at radio frequencies. Single-post, double-post and triple- (or more) post tubular types are also made so that space and cost can be saved and more efficient decoupling obtained. The construction of

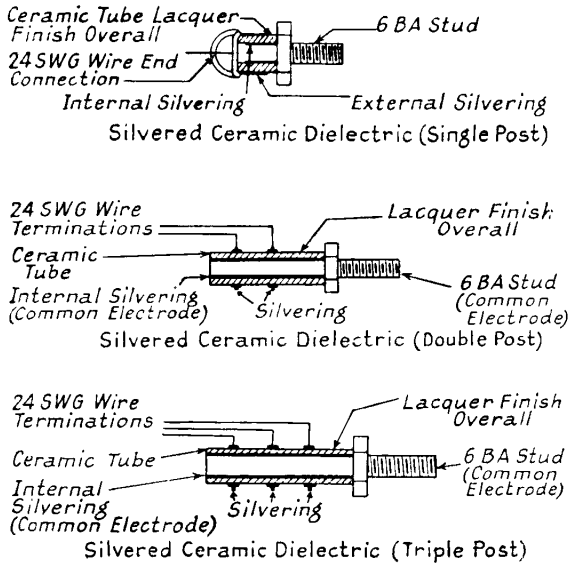


FIG. 6.13. CONSTRUCTION OF POST-TYPE CERAMIC CAPACITORS

typical single-, double- and triple-post high-permittivity capacitors is shown in Fig. 6.13.

Feed-through or bush-mounting types are also made in which the capacitor becomes an integral part of the metal chassis, through which it projects, simplifying earthing problems at radio frequencies. Lead inductance is virtually eliminated because of the small physical size and the fact that the inductance is in series with the inner electrode rather than a new path to earth. A typical construction is shown in Fig. 6.14. Capacitors are also available as "stand-off" types, one end being screwed directly to the chassis as the earth connection.

Disc types are also made for use in sub-miniature and miniature assemblies, where their small size adapts them for wiring directly across the required points. Miniature button types are also made in various shapes. "Cascap" high-permittivity capacitors, made by Plessey, have

values ranging from 0·0005 to 0·01 μF, operating at up to 500 V d.c. (or 300 V a.c.). The insulation resistance of the special coating is high, averaging 10^5 MΩ, and wax impregnation is unnecessary. The breakdown voltage is high—about 4,500 V d.c. for most values—and a range of suppressor capacitors is available. Dimensions lie between (approximately) 0·4 and 0·9 in. diameter, and 0·14 and 0·19 in. thickness.

All these types are generally used for by-passing in low-power r.f. transmitter circuit and in communication and other receivers.

For larger capacitance values than can be produced with the tubular types, flat types are being made. Machines have been developed

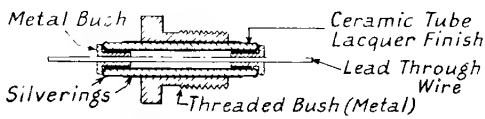


FIG. 6.14. CONSTRUCTION OF FEED-THROUGH CERAMIC CAPACITOR

capable of producing very thin films by band casting processes similar to that described below.

The ceramic mix, prepared as described previously, is passed through an extruding hopper on to a stainless-steel belt which is moving slowly at a few feet per minute. The ceramic "slip" is very carefully prepared and ball-milled for at least 24 hr. Thorough mixing and ball-milling is essential where thin films are required, and the material is usually passed through a 300-mesh sieve, chemical cleanliness being maintained throughout the whole of the process. The slip is fed into an extruding hopper over the moving belt and levelled on the moving belt by a doctor bar. It then passes through a drying oven where it is dried sufficiently to be removed from the belt and cut into suitable sections. The sections are then fired on zircon or similar plates with 4 or 5 hr preheating, an hour at the maximum temperature and 3 or 4 hr cooling.

In other methods a small bottomless box, with a "gate" in the trailing side, contains the slip. This box is drawn along a glass plate, leaving behind a thin layer of slip, the thickness of the layer being controlled by the depth of the gate and the speed of drawing. The movement of drawing must be absolutely constant in speed; films as thin as 0·005 cm have been drawn by this method.

The main difficulty in the manufacture of these thin, fragile flat plates is curling or warping, which precludes their assembly as stacked capacitors. They are usually silvered by paste silvering methods and fired in the stacked form, palladium and platinum plates being used to withstand the high temperatures. The electrode leads are then soldered on to the ends, the stacks being pre-heated sufficiently to avoid cracking by thermal shock. This type of capacitor is approaching the production stage in the U.K.

Ceramic-dielectric Transmitter Capacitors

Ceramic capacitors are designed for use in medium-power oscillator and transmitter circuits. Their high stability and small size, compared with an air-dielectric capacitor, make them suitable for use in tank and matching circuits, but they are equally useful as by-passing, blocking or coupling capacitors. A most valuable feature is their ability to withstand high voltages for long periods without deterioration.

Where high voltages are used, voltage gradients at the edges of electrodes can be very troublesome. For working voltages over 3·5 kV, capacitors are provided with a glazed ceramic rim which reduces the voltage gradient at the edges of the electrodes and avoids corona losses which can lead to premature breakdown. The shape and position of the electrodes are determined by the rim and no adjustment of capacitance is possible, as grinding off the metallizing negatives the very careful design for maximum voltage stress loading. Standard tolerances are plus or minus 15 per cent, but plus or minus 10 per cent can be made. The electrodes consist of coatings of fired-on silver of adequate thickness and high conductivity, capable of withstanding a high current loading. The terminal tags and other connections are soldered to the electrodes, the contacts being made sufficiently large to prevent local overheating on full-load current.

Tubular construction is used where low volt-ampere ratings are required, while the pot type of construction is used for capacitors of medium kVA rating. For high-voltage or high-power or current applications, the capacitors are assembled in banks in series or series-parallel combinations. For high-rating capacitors the dielectric is in the form of a heavy ceramic tube with carefully designed glazed ceramic sheds at each end. This open tubular construction allows free air ventilation, and forced air cooling can be used if a higher power-handling capacity is required.

Various types of construction are used, depending on the ratings required, and reference should be made to the manufacturers for particular requirements. Typical examples are shown in Fig. 6.15.

Base-metal-electrode Ceramic Capacitors

The base-metal-electrode capacitor consists of interleaved layers of ceramic and metal sintered to form a solid mass. The ceramic is barium titanate so modified that it can be sintered under strongly reducing conditions without becoming conductive. Its permittivity is about 2,000, which, with a dielectric thickness of 0·010 in., gives a capacitance per unit volume of 4 μF/in.^{3} with d.c. working voltage of about 300 V (breakdown better than 1,000 V up to 150°C). The metal electrodes are formed from nickel.

The dielectric thickness can be reduced to 0·003 in. to give a

capacitance per unit volume of 30 μF/in.^{3} with a d.c. working voltage of about 50 V. The RC product is greater than 100 at room temperature and falls to 0·5 Ω-F at 150°C. 1,000 hr lives can be obtained at 150°C with half the room-temperature working voltage applied.

The application of the d.c. working voltage at room temperature lowers the capacitance by 20 per cent. At temperatures above 80°C

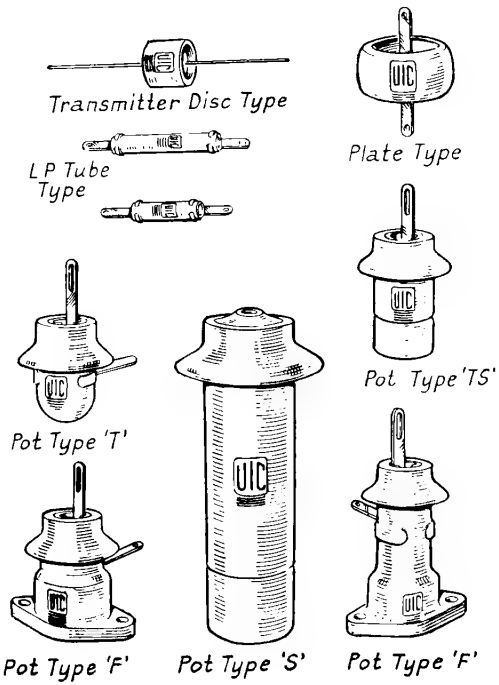


FIG. 6.15. TYPICAL EXAMPLES OF CERAMIC TRANSMITTER CAPACITORS

the capacitance is independent of voltage. A capacitor of value 30 per cent above nominal at room temperature will be 40 per cent above nominal at 45 C (maximum value), nominal at + 90° and − 10°C, and 50 per cent of nominal at + 150° and − 40°C.

The power factor (tan δ) is 0·04 at − 40°, 0·01 at 80° and 0·03 at 150°C (1,000 c/s).

The loss increases with alternating voltage to a maximum of 0·05 at 100 V and diminishes again at higher voltages. The capacitance increases by 20 per cent and then diminishes under the same conditions (300 V working at 1,000 c/s).

Single-block units with capacitances between 0·02 and 1 μF are made. Larger-value capacitors are usually built from 1-μF units.

Magnesium-silicate Capacitors

Experimental stick-type capacitors have been made by the Philips Company in Holland in which a central metal electrode is inserted into a magnesium-silicate tube with an outer metal tube fitted. This assembly is heated and drawn down like wire until the required diameter is obtained. The length of "stick" is cut off according to the capacitance required. A small portion of the outer tube is cleaned off at the ends and connections are made to the electrodes.

Experimental capacitors produced are about $1\frac{3}{4}$ in. long by $\frac{1}{32}$ in. diameter with a capacitance of approximately 100 pF.

Barrier-layer Ceramic Capacitors

Barrier-layer capacitors are made from dielectrics whose particles exhibit high permittivity as a result of continuous layers of low-loss

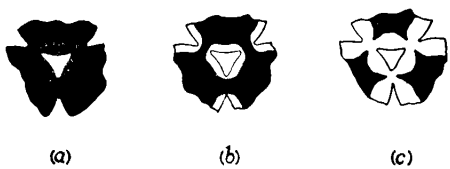


Fig. 6.16. Model Showing Formation of Intergranular Barrier-layer Dielectric from Ceramic Consisting of Sintered Spheres

(*a*) Reduced ceramic
(*b*) Partially re-oxidized but still with low resistivity
(*c*) Barrier layers formed

dielectric enclosing regions of high conductivity. Ceramic dielectrics containing titanium dioxide can be reduced and partially reoxidized so that the reduced ceramic behaves as an *n*-type semiconductor, and according to the porosity, barrier layers are formed either between the ceramic grains or on the ceramic surface. Fig. 6.16 shows the formation of intergranular barrier-layer dielectric from ceramic sintered spheres.

The preparation of the basic ceramic is similar to that described in the manufacture of ceramic capacitors, i.e. mixing, calcining, milling, pressing ito thin discs and sintering. At this stage the capacitors are reduced in hydrogen or carbon monoxide at about 1,300° C. (This process may sometimes be combined with the previous sintering process.) The thin discs are then partially reoxidized and silver contacts fired on. They are then finally reoxidized, usually in air, between 600° and 800° C. Connecting leads are then attached and the disc is encapsulated to prevent moisture penetration, as barrier-layer capacitors are particularly sensitive to the ingress of water.

Materials from which capacitors can be made are titanium dioxide, barium titanate, barium-strontium titanate, etc. Additions of bismuth titanate to strontium titanate may result in dielectrics with very high permittivity and low dielectric loss angle. Some of these materials may have effective permittivities of 200,000 and loss tangents of 0·07 at

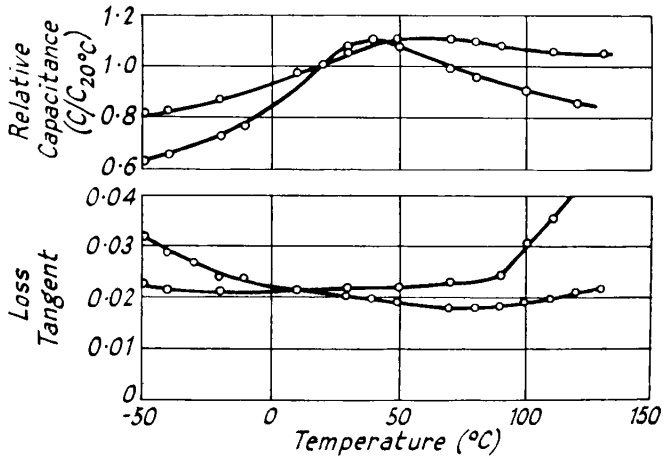


FIG. 6.17. VARIATION OF DIELECTRIC PROPERTIES WITH TEMPERATURE FOR TWO COMMERCIAL BARRIER-LAYER CAPACITORS

1 kc/s. The resistivity of these capacitors is non-ohmic and obeys the law

$$\rho = \rho_0 E^{-\gamma}$$

where E = field strength,

ρ_0 = resistivity at $E = 1$ V/cm (usually 1 to 5 $\times$ 10^7),

γ = constant (3 to 5).

The fall in resistivity with increasing field causes a rise in the loss tangent, and this, together with the leakage current, limits the working voltage of practical capacitors to about 3 V. Typical barrier-layer capacitors rated at 3 V have volume factors of 35 μF/in.^{3}, and Fig. 6.17 shows typical curves of temperature dependence with permittivity and loss tangent. The Curie point in both types of capacitor is approximately 50°C.

GLASS-DIELECTRIC CAPACITORS

Glass has been described as a "super-cooled liquid solution" and also as "an inorganic product of fusion which has cooled to liquid conditions without crystallizing." There are many types and varieties in use—it

has been estimated that, at the moment, 500 to 600 varieties of glass are available. Domestic and commercial glass consists fundamentally of silica in the form of sand fused into a translucent mass by the assistance of fluxing oxides, whose purpose is to lower the melting point of the mixture. The properties of the fundamental base can be adapted to special requirements by the inclusion of one or more of many oxides and certain halides; e.g. the addition of alumina improves the mechanical strength, litharge varies the optical characteristics, and boric oxide increases the resistance to thermal shock. These and other effects can be obtained by skilful mixing of the ingredients used in the making of glass.

Glass which has been subjected to heat and work cools in a condition of strain; if it is reheated to a temperature approaching, but less than, the softening point it will lose this strain and become annealed. The temperatures between which this phenomenon occurs are referred to as the annealing "range"—there is no fixed temperature at which a glass suddenly becomes soft or molten. For practical purposes, the "softening point" is regarded as the temperature at which the glass may be deformed without cracking.

Glass maintained at a high temperature for an extended period may suffer molecular and atomic regrouping and become crystalline and devitrified. The melting point of silica varies according to the form in which it is used, but will be generally between 1,600 and 1,700°C. This is an inconveniently high temperature for commercial working, and the common practice is to reduce the fusing point very considerably by the inclusion of the oxides (generally in the form of carbonates) of the alkali metals. These alkali-metal silicates or glasses are not stable or durable in themselves, being freely attacked by the mildest of chemicals, and are frequently soluble in water. It is, however, easy to include a quantity of lime or magnesia in order to obtain the necessary durability, without sacrificing the conveniently low softening temperature.

Low-power-factor glasses having suitable characteristics, such as low temperature coefficient, are being developed for use as capacitor dielectrics. In general, for electrical purposes the glass should contain little or no alkali-metal oxides in the primary base (silica). A considerable amount of the glass used for electrical work has boric oxide as a flux and is referred to as a "boro-silicate" glass.

The lowest-power-factor glass known is the pure vitreous silica which has a quoted value $\tan \delta = 0{\cdot}000115$. Glasses of the boro-silicate type containing 4 per cent or less of alkali metal oxides have a $\tan \delta$ of the order of 0·005 to 0·007 at 1 Mc/s, with a permittivity of 4·18. The power factor of glass generally increases with increasing temperature, increasing more rapidly with temperature for low frequencies than for high frequencies. The following results (due to Hoch) are representative

of the values obtained on a Pyrex Chemical Resistance glass at 500 kc/s—

	Loss Angle tan δ	*Permittivity* ε
20°C	0·0042	4·9
74°C	0·007	5·0
125°C	0·012	5·0

The permittivities of glass mixtures range from about 3·7 (for a pure silica glass) up to 18 or 20, fairly high permittivities being obtained in glass containing the oxides of lead, potassium and silicon. There is a tellurium glass with $\varepsilon = 26$ and a low loss-angle.

For use in capacitors at high frequencies the glass used will generally contain one of the heavy metals (barium, strontium or lead) as oxides and will have low alkali-metal content. If an alkali metal is used, it should preferably be potassium. Glasses made in this manner can give fairly high permittivity with reasonably low power factor. Borosilicate glasses now being made show relatively low values of temperature coefficient of power factor, permittivity and resistivity, and are also characterized by low coefficients of thermal expansion, of the order of $3{\cdot}2$ to $4{\cdot}0 \times 10^{-6}$. They have a high surface stability to chemical and atmospheric attack and good thermal stability. Temperature coefficients are positive and decrease at the higher frequencies.

The dielectric strength of glass is high, decreasing with increase of temperature and frequency, and as the time of application of the potential increases.

Stevels* has identified four separate mechanisms of dielectric loss in glass; these are

(*a*) Conduction loss.
(*b*) 'Dipole' relaxation loss.
(*c*) Deformation loss.
(*d*) Vibration loss.

(*a*) and (*b*) are both attributed to movements of the alkali ions through the relatively rigid network of the network-forming ions, e.g. the silicon and oxygen ions, and these losses are called collectively the migration losses. (*c*) is attributed to small changes or deformations in the network itself. The vibration loss, (*d*), is a resonance phenomenon between the applied electric field and the vibrations of all the ions about their rest positions. Fig. 6.18 shows schematically the frequency regions in which these loss mechanisms operate at room temperature.

* Stevels, J. M. "The electrical properties of glasses." *Handbuck der Physik* XX, p. 372, Springer-Verlag (1957). "Dielectric Verluste des Glases." *Glastechnische Berichte*, **26** (1953), 227.

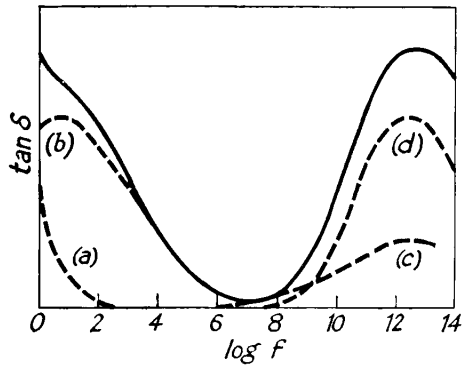


FIG. 6.18. STEVELS'S SCHEMATIC REPRESENTATION OF THE FOUR REGIONS OF DIELECTRIC LOSS IN GLASS AND THE RESULTANT LOSS CURVE OVER A WIDE RANGE OF FREQUENCIES AT ROOM TEMPERATURE

(*a*) Conduction
(*b*) Dipole relaxation
(*c*) Deformation
(*d*) Vibration
——— Resultant

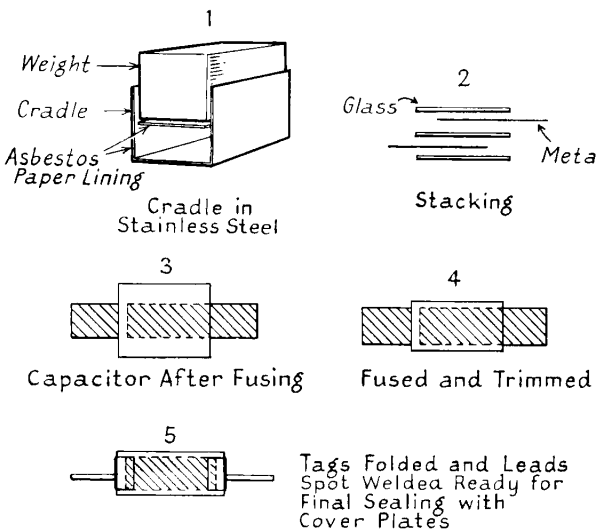


FIG. 6.19. FABRICATION OF EXPERIMENTAL GLASS CAPACITORS

Construction and Behaviour of Glass-dielectric Capacitors

Glass capacitors have many advantages, including wide temperature range of operation (− 55 to + 200°C), low power factor, high insulation resistance and high breakdown strength, comparing favourably with mica, particularly at high temperatures. The variation of capacitance with temperature is repeatable or cyclic and the spread of temperature coefficient very small. The capacitors can be made in block construction completely sealed in glass.

There are three ways in which such capacitors can be made, depending on the quantities to be produced—

(1) By blown glass bubbles, broken into small pieces and annealed.
(2) By using thin cover glass plates (such as those used for microslides).
(3) By continuous extrusion of flexible glass ribbon.

The first two methods are used for experimental capacitors, the third for large-scale continuous production. Experimental capacitors have been made from glass prepared by the first two methods by assembling as shown in Fig. 6.19.

The electrodes are aluminium foil. Copper cannot be used owing to the formation of cupro/cupric oxide, whilst silver presents difficulty owing to diffusion, with formation of yellow silver silicate above 600°C. Gold can be used successfully, and gold foil is readily available in thin sheets. The capacitors are assembled and fired in a cradle or open-ended box of stainless steel lined with asbestos paper, as shown in the diagram. The glass plates and metal foil are stacked, alternate pieces of the foil being extended beyond opposite ends of the glass plates. The assembled element is covered by a piece of asbestos paper surmounted by a floating weight of approximately 100 g per square inch of surface area.

The capacitor assembly is fired in air when using gold foil and in an atmosphere of nitrogen when using aluminium foil. The assembly is heat-soaked at the softening point of the glass, which slowly takes up its final position pushing out unwanted air. The temperature is then increased to fusing point, when a solid mass is formed.

Terminals may be provided at this stage either by spot welding the overhanging tips of foil to a silver brass wire, or by forming a silver clamp. The capacitor assembly with tags is then placed between two thicker plates of similar glass sufficiently large to overhang on both sides and ends. This is then fired under a weight, as before, which causes the overhang to soften and meet, forming a complete envelope round the assembly.

Capacitance/temperature and power-factor/temperature curves are given in Fig. 6.20 for typical experimental capacitors assembled in this

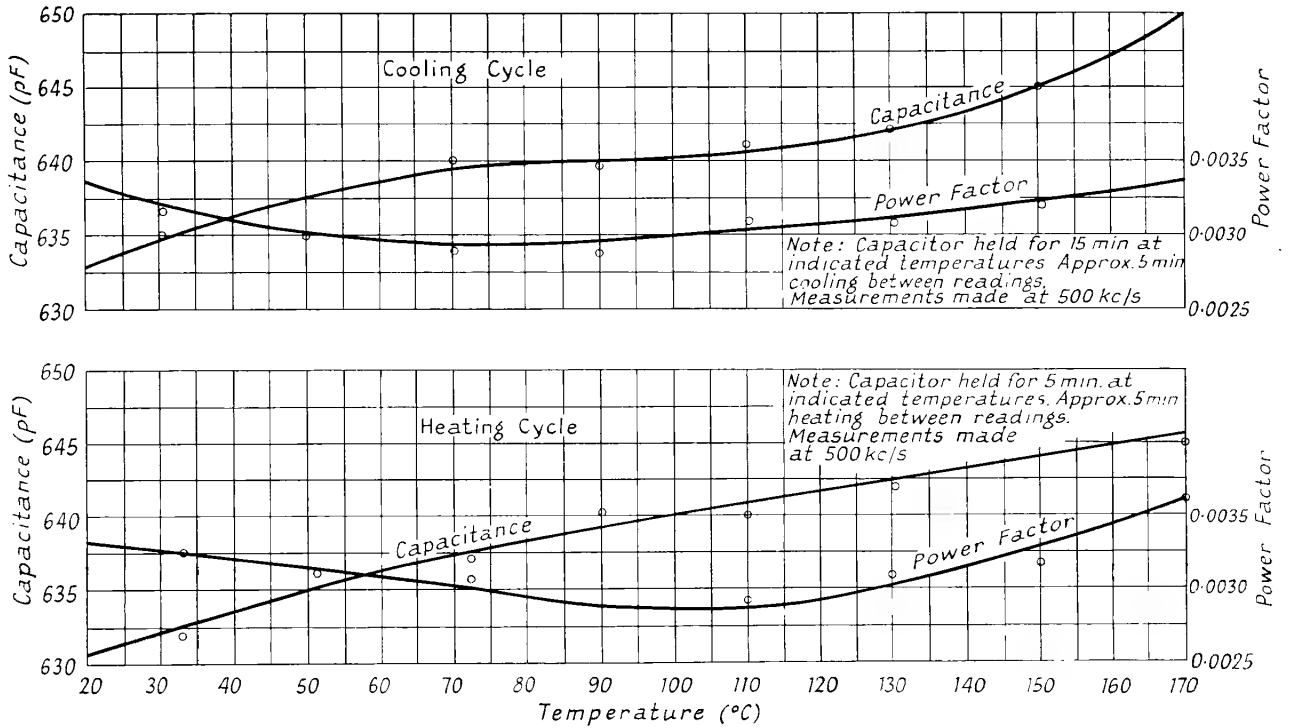

Cooling Cycle
Capacitance
Power Factor
Note: Capacitor held for 15 min at indicated temperatures Approx. 5 min cooling between readings. Measurements made at 500 kc/s
Capacitance (pF)
Power Factor
650
645
640
635
630
0·0035
0·0030
0·0025
Heating Cycle
Capacitance
Power Factor
Note: Capacitor held for 5 min. at indicated temperatures. Approx. 5 min heating between readings. Measurements made at 500 kc/s
20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
Temperature (°C)

FIG. 6.20. EXPERIMENTAL GLASS CAPACITOR CHARACTERISTICS

way using aluminium foil, fused in an atmosphere of nitrogen at 600°C and using glass consisting of 40 per cent silica and 50 per cent lead oxide with the necessary fluxing oxides.

Capacitors made by the Corning Glass Company in the U.S.A. have the typical sizes and voltage ratings at 85°C given in Table 6.3.

TABLE 6.3

Size (in.)			Capacitance (pF)	
Length	Width	Depth	500-V Rating	300-V Rating
$\frac{7}{32}$	$\frac{3}{8}$	$\frac{3}{32}$	150	240
$\frac{5}{16}$	$\frac{1}{4}$	$\frac{3}{32}$	510	1,200
$\frac{15}{32}$	$\frac{13}{16}$	$\frac{1}{8}$	3,300	5,100
$\frac{13}{16}$	$\frac{13}{16}$	$\frac{1}{8}$	5,100	10,000

An important feature of the glass capacitor is that the casing material can be made of the same low-power-factor glass—the capacitor need not be encased in plastic or other material with higher losses. It is usually suspended in the wiring, being small and light, so that its performance is a function only of the dielectric properties of the glass.

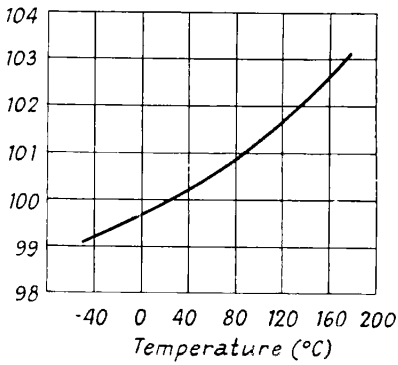


FIG. 6.21. CAPACITANCE/TEMPERATURE CURVE FOR GLASS CAPACITOR

The variation of capacitance with temperature is shown in Fig. 6.21 and the temperature coefficients of capacitance, derived from Fig. 6.21, are given in Fig. 6.22.

At 200°C, the decrease of dielectric strength with increase of temperature is about 5 per cent of the value at room temperature. The *RC*

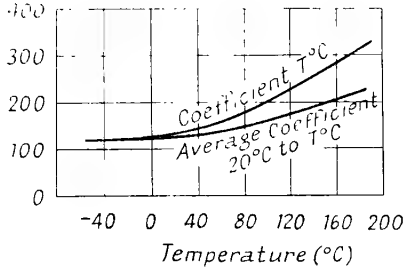
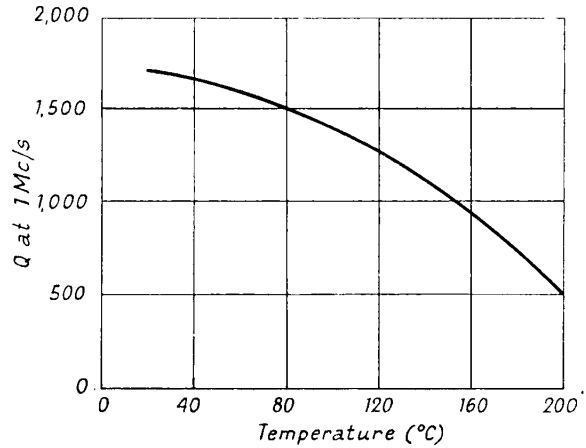
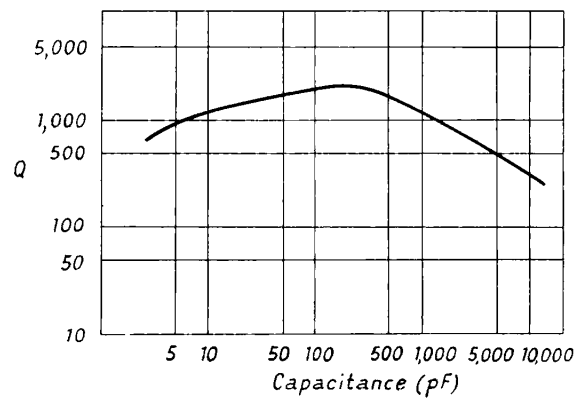


FIG. 6.22. TEMPERATURE-COEFFICIENT/TEMPERATURE CURVE FOR GLASS CAPACITOR





Corning Glass Co.

FIG. 6.23. VARIATION OF *Q* WITH TEMPERATURE AND CAPACITANCE FOR GLASS CAPACITOR

product, as for most inorganic insulating materials, decreases approximately exponentially with increase of temperature—for these capacitors it is about one order of magnitude per 30 C; at 75°C it is about 50,000 ΩF. The variation of Q with temperature and with capacitance is shown in the graphs of Fig. 6.23.

Glass capacitors are also of interest for use in medium-power transmitters, where their characteristics compare favourably with mica. They can be scaled to resist moisture penetration.

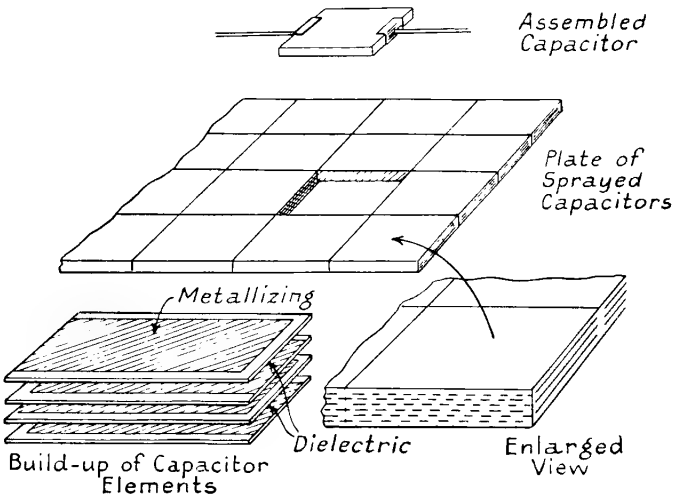
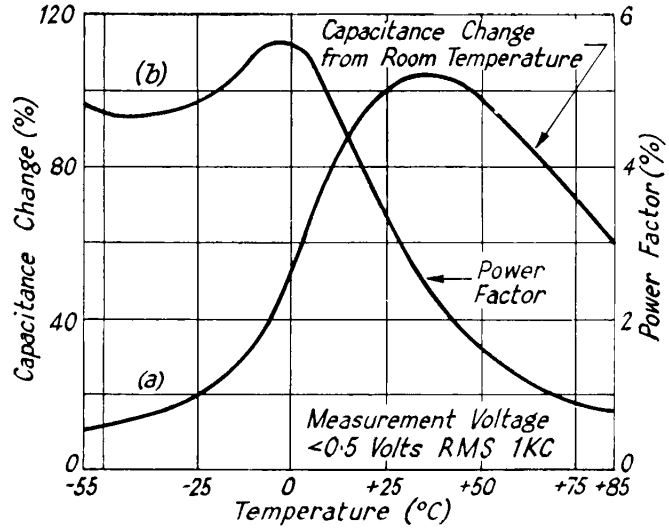


FIG. 6.24. GLAZE-DIELECTRIC CAPACITORS

VITREOUS-ENAMEL OR GLAZE-DIELECTRIC CAPACITORS

Capacitors have been made in the U.S.A. in which layers of vitreous enamel are alternated with layers of electrode metal (squeegeed through suitable masks), with semi-drying between each spraying. The dielectric enamel is a mixture of consistency suitable for spraying, consisting of silica, alkali oxides and fluorides, with lead and other oxides. Many capacitors are made at once by using a large area and cutting up as shown in Fig. 6.24, the masking being arranged so that the silver electrodes are overlapped alternately at each end of the unit. The capacitors are then fired and leads soldered on.

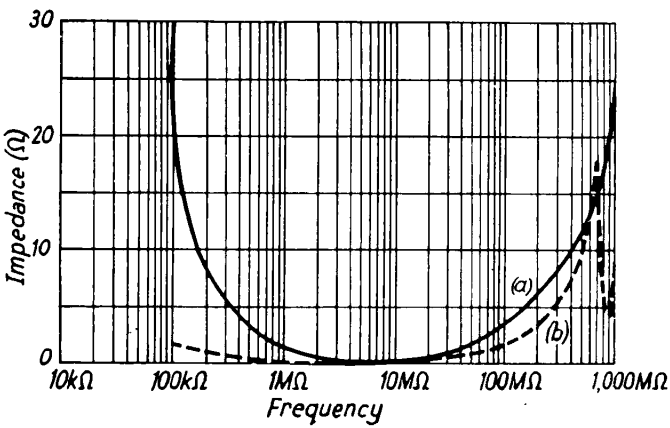
The characteristics of capacitors produced in this way are good. They have a positive temperature coefficient of approximately 105 ppm/°C. They can be rated for 500-V operation and have a capacitance of the order of 0·01 μF/in.^{3}. Leakage current is negligible up to 180°C, and



Sprague Electric Co.

FIG. 6.25. CAPACITANCE/ AND POWER-FACTOR/TEMPERATURE CHARACTERISTICS OF 0·75-μF 25-V HIGH-PERMITTIVITY CAPACITOR

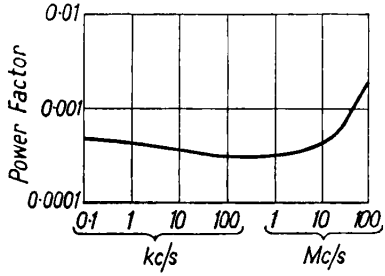
(*a*) Change of capacitance from that at room temperature
(*b*) Power factor
Maximum size of capacitor, $\frac{1}{2}$ in. × $\frac{1}{2}$ in. × $\frac{1}{8}$ in.
Measurement voltage, < 0·5 V r.m.s. at 1 kc/s

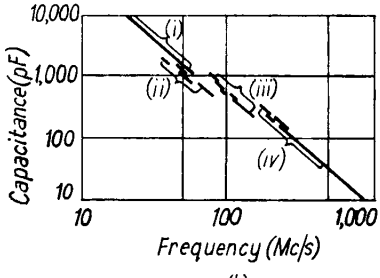


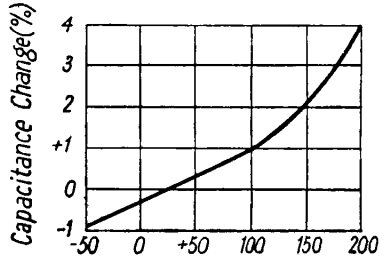
Sprague Electric Co.

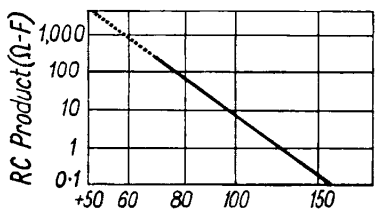
FIG. 6.26. IMPEDANCE/FREQUENCY CHARACTERISTICS OF HIGH-PERMITTIVITY CAPACITORS

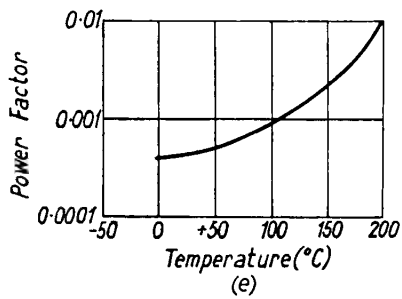
(*a*) 0·1-μF single-layer capacitor, 0·5 in. × 0·45 in.
Leads, $\frac{1}{4}$-in. long, copper foil
(*b*) 0·75-μF ten-section capacitor, 0·45 in. × 0·45 in.
Leads, 1·8 in. long, copper foil
The absence of antiresonance up to 1,000 Mc/s makes this construction useful for by-pass and decoupling applications











Vitramon Corporation

FIG. 6.27. CHARACTERISTICS OF HIGH-PERMITTIVITY CAPACITORS

(*a*) Power-factor/frequency
(*b*) Capacitance/frequency

	Length	*Breadth*	*Depth*
(i)	$\frac{37}{64}$ in.	$\frac{37}{64}$ in.	$\frac{1}{4}$ in.
(ii)	$\frac{13}{32}$ in.	$\frac{13}{32}$ in.	$\frac{5}{16}$ in.
(iii)	$\frac{1}{4}$ in.	$\frac{1}{4}$ in.	$\frac{7}{64}$ in.
(iv)	$\frac{3}{8}$ in.	$\frac{1}{4}$ in.	$\frac{1}{16}$ in.

(*c*) Capacitance/temperature. The temperature-coefficient retrace is essentially absolute, any variations being limited to 0·05 per cent of the curve
(*d*) *RC*-product/temperature
(*e*) Power-factor/temperature

they can be used at 125°C continuously. Their performance is comparable to that of mica capacitors through the range of radio frequencies and they can withstand climatic conditions well. Their re-trace characteristics are excellent.

In one U.S.A. process* the capacitors are fabricated in multiples on platens approximately 1 ft square. The platens move through the various operations by means of a conveyor chain making as many trips around the machine as necessary, depending upon the number and thickness of the dielectrics required. The platens proceed through a drying tunnel to the opposite end of the machine, where an electrode is applied in a multiple pattern by the silk-screen method. The platen moves through another drying tunnel which drys the applied electrode and returns it to the spray booth to receive the next coat of dielectric material. This sequence is repeated as many times as necessary to build up the required number of dielectrics and corresponding electrodes. The platen is then taken from the machine through a series of cutters which dice the material into the shape desired. The equipment is capable of manufacturing capacitors in the range from 15 pF to several thousand picofarads. Typical characteristics are shown in Figs. 6.25 and 6.26.

In another U.S.A. process,† capacitors are manufactured from a fritted glass base material which, after pulverization, is suspended as a slurry, cast as dielectric films and laminated with silver electrodes of known area to achieve desired capacitance. Subsequent hardening techniques reduce the laminated structure to a firm, solid block which can be worked with ordinary tools to provide for the interconnection of alternate electrodes and the insertion of silver wire terminals. When fired at high temperatures, the unit becomes a homogenous, monolithic block of porcelain which has no strata and which is completely non-porous, bonded and hermetically sealed. Typical characteristics are shown in Fig. 6.27.

* Sprague Electric Co.
† Vitramon Corporation.

Chapter 7

CAPACITORS WITH PLASTIC AND LOADED-PLASTIC DIELECTRICS

Polystyrene-film Capacitors

The most important property of the polystyrene-film capacitor is its extremely high insulation resistance. These capacitors also have extremely low dielectric absorption, so that they are able to store an electric charge and to deliver it completely when required. This property is of value in such applications as

Radio-frequency tuned circuits.
Digital computing apparatus (as storage capacitors).
Measurements of ionization currents in radioactive materials.
Dosage measurements in X-ray therapy.
Long-time-constant circuits.

The percentage absorption, compared with other dielectrics in some measurements made by the Royal Aircraft Establishment, is shown in Table 7.1.

Table 7.1. Percentage Absorption in Various Dielectrics at Various Temperatures

Dielectric	Short-circuit Duration (min)	Charging Pulse Duration (ms)	Open-circuit Duration (min)	Percentage Absorption at Temperature (°C)							
				−60°	−40	−20	0°	+20	+40	+50	+70°
Polystyrene	1	1	1	0·09	0·11	0·15	0·17	0·18	0·17	0·17	0·17
Paper + petroleum jelly	60	10	1	3·3	2·2	1·9	1·7	1·9	3·0	5·0	
Paper + chlorinated naphthalene	60	10	1			2·3	2·0	2·6			
Mica, silvered	1	1	1					3·85			
Mica, clamped	1	1	1					1·95			

The power factor is low—about 0·0002. The capacitance stability is good and the temperature coefficient is from − 100 to − 200 ppm/°C. There is a slight change in temperature coefficient at about room temperature as shown in Fig. 7.1.

The main disadvantage for Service use is the limited range of temperature over which the capacitor may be used—it should not normally be

operated over 60°C, although some low-capacitance types can be operated at up to 85°C. The properties of polystyrene are as follows—

Power factor (tan δ) (up to 10^9 c/s)	0·0002 to 0·0005
Dielectric strength, 0·003 in. thickness	3,000 V/mil
0·002 in. thickness	4,000 V/mil
Permittivity (up to 10^9 c/s)	2·5 to 2·7
Surface resistivity	10^{16} Ω per square
Volume resistivity	10^{17} to 10^{19} Ω-cm
Specific gravity	1·05
Tensile strength	11,000 lb/in.^{2}
Elongation at break (room temperature)	4%
Coefficient of linear expansion	0·00001 per °C
Softening temperature	Approximately 85°C

Polystyrene is soluble in benzene, toluene and xylene; its chemical formula is $(C_6H_5—CH—CH_2)_n$.

For use in capacitors the polystyrene film must be extruded flat and

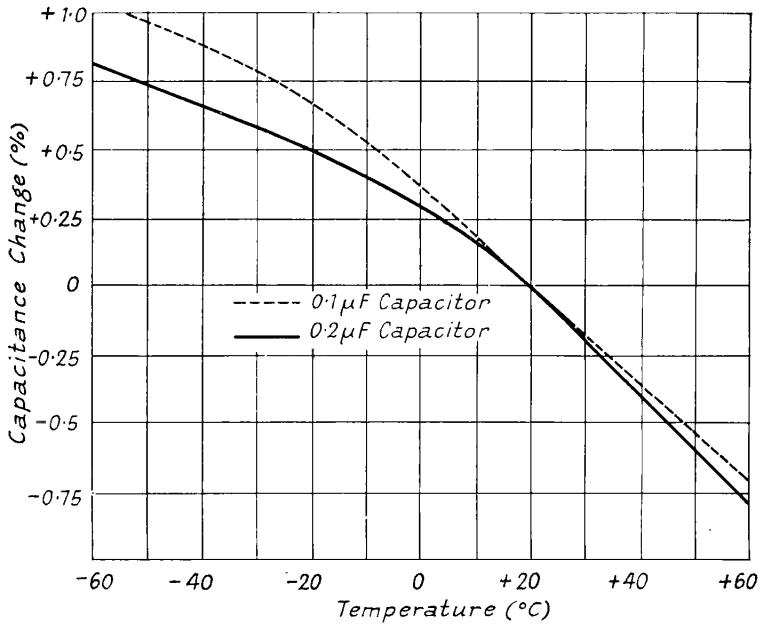
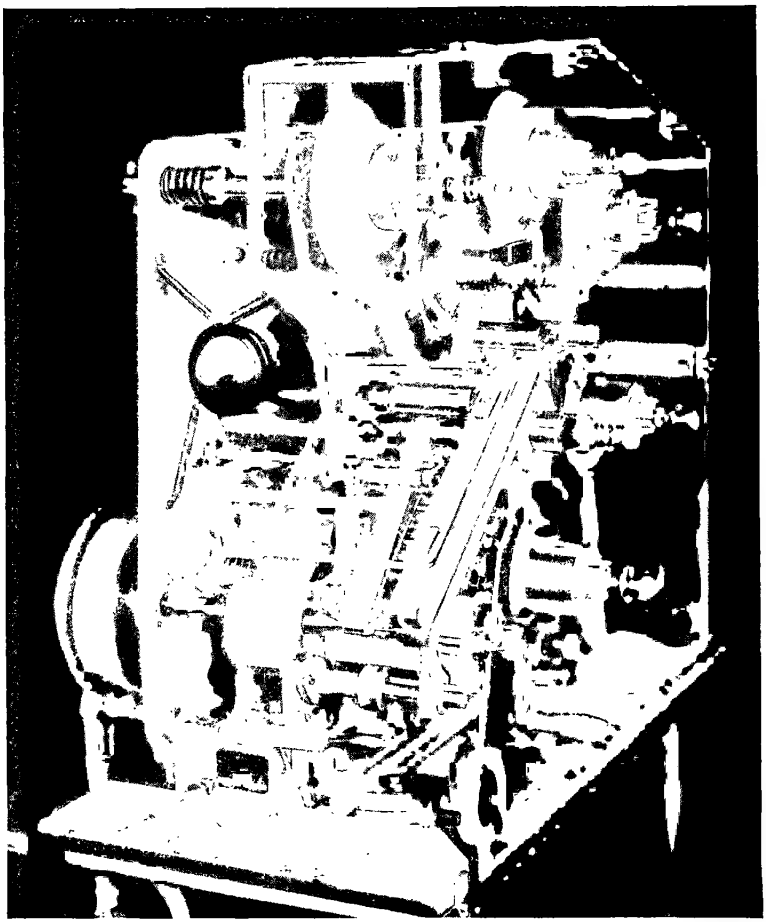


FIG. 7.1. CAPACITANCE/TEMPERATURE CURVES FOR POLYSTYRENE CAPACITORS

free from pinholes, and many difficulties have been overcome in fulfilling this requirement. Film for capacitors is made from polystyrene granules by extruding a heated tube of polymer which is then spread out and stretched in two directions at right angles and cooled in the

stretched state. The cooling rate is carefully controlled, and air jets are commonly used. After this process the molecular chains of the polystyrene lie predominantly in the plane of the film, and at normal



T.M.C. Ltd.

FIG. 7.2. ENCLOSED FILM-WINDING MACHINE FOR POLYSTYRENE FILM

temperatures the arrangement remains "frozen-in" indefinitely. This orientation will, however, rapidly relax at a temperature between 90°C and 100°C, and if the film is not constrained in some way it will contract in its own plane and become thicker, thus reducing the capacitance.

To allow for this, during manufacture heat treatment above the relaxation temperature is applied after the film has been wound with aluminium-foil electrodes. This ensures that the film contracts firmly into contact with the electrodes, eliminates voids or spaces between the electrodes, seals the ends of the winding and results in a stable capacitor. Capacitors made in this way are often referred to as "shrunk" capacitors. Great difficulty may be experienced during winding because the films acquire static charges which collect extraneous dust particles, and these embed themselves into the film, causing short-circuits and consequent failures. One method of overcoming this is by the use of a high-voltage transformer connected to a metal comb with the teeth facing the film and with a flat earthed metal plate mounted under the comb.

An alternative, and better, arrangement is to enclose the winding machine in a transparent plastic case as shown in Fig. 7.2.

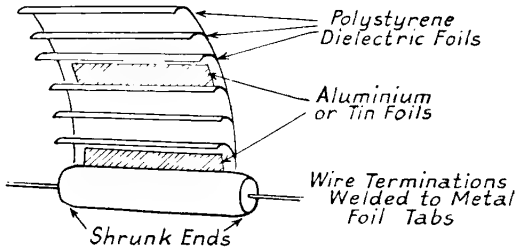
In addition, the room in which the winding machines are operated is usually air conditioned. More than one polystyrene film is usual, to increase the dielectric strength, and the metal foil used is almost invariably aluminium, although tin has been used. The contact between the metal foil and the lead-out foil is most important and in some cases welded joints are made to ensure perfect contact. It is essential that chemical cleanliness be maintained throughout the manufacture of this type of capacitor, and it is particularly important that contamination of the film by grease or oils, or even dandruff from the operator's hair, should be avoided. Some constructions of typical "shrunk" capacitors are shown in Fig. 7.3. Fig. 7.4 shows more clearly the construction of the rolled-foil type.

Cellulose-acetate and Cellulose-acetate-butyrate Capacitors

Cellulose acetate and butyrate were once used as dielectric films for capacitors, but their electrical characteristics are inferior to those of polystyrene. Their losses are lower than paper, but rise to a high value at approximately 100 Mc/s. The power factor is similar to that of paper, i.e. 0·01 to 0·03, and the permittivity 3·0 to 4·0, decreasing with frequency up to about 1 Mc/s. As the technique for the manufacture of paper dielectrics was known and paper was available, these dielectrics were not used in quantity, and are not now likely to be used in view of modern development of plastic dielectrics such as Melinex film or Terylene.

Cellulose Acetate Cross-linked with Di-isocyanate

An attempt to overcome some of the limitations of cellulose acetate by cross-linking it with metatolylene di-isocyanate has been made in the U.S.A. by the Sprague Electric Company. The main objective is to



Tubular (Insulated) Form

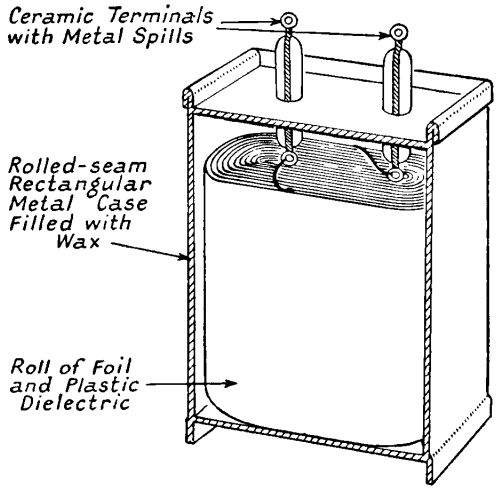


FIG. 7.3. CONSTRUCTION OF POLYSTYRENE-FILM CAPACITORS

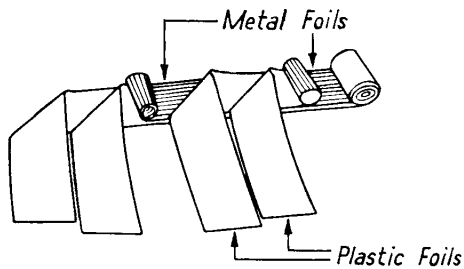


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FIG. 7.4. POLYSTYRENE CAPACITOR ROLLS
Showing wound construction

increase the upper working limit of temperature, and capacitors are reported to have been operated at 100°C to 150°C.

Epoxy (Ethoxylene-dielectric) Capacitors

Experimental thin films of epoxy resin were prepared at the Royal Aircraft Establishment some years ago for measurement of moisture permeability and were found to be approximately 30 per cent better than polythene in their resistance to moisture penetration. They are, however, little used as capacitor dielectrics as the power factor is too high. Tests on breakdown voltage between spheres under oil gave values better than those of mica. The films were only prepared experimentally in the laboratory and when metallized showed short-circuits due to pinholes.

Polytetrafluoroethylene (P.T.F.E.) Capacitors

P.T.F.E. is an excellent high-temperature material and a promising dielectric, having electrical characteristics similar to polystyrene at ordinary temperatures, but capable of operating, and retaining these electrical properties, up to about 250°C. There are two methods of producing thin films suitable for experimental capacitors—by shaving film from the solid roll, and by casting. The main defect in the shaved film is the large number of pinholes, and it is also very difficult to produce films of a thickness below 0·002 in. A process of casting has been developed in which a highly polished metal surface is coated with a colloidal aqueous dispersion of P.T.F.E., force dried and sintered until a continuous film is formed. When cold, the film is stripped off. Films made in this way have fewer pinholes than the shaved film. Low breakdown points experienced may not necessarily be due to pinholes or voids, as foreign particles may be carbonized at the sintering temperature. High-temperature miniature capacitors have been made up to about 0·05 μF.

Other films have been made by extrusion from special paste compounds which possess the inherent properties of P.T.F.E. Various metallizing processes have also been evolved, both in the U.K. and the U.S.A. In the United Kingdom 12-μm film is being made by passing a metal band through P.T.F.E. latex, firing and stripping off, afterwards metallizing with copper. A disadvantage which is becoming apparent from experience of P.T.F.E. capacitors is that of poor corona resistance. The life of P.T.F.E. capacitors at a continuous high voltage is reduced if corona is present. Another difficulty which arises is the variation in dielectric strength when measurements are made at different points over the surface of the film. The softening temperature also varies greatly with applied pressure. Whilst the electrical characteristics are excellent for high-temperature operation the material is as yet expensive.

Polychlortrifluoroethylene (P.C.T.F.E.)

P.C.T.F.E. is known as "Kel F" in this country and as "Hostaflon" on the Continent. Detailed studies of experimental films for capacitor dielectrics have not yet been made. The main advantage of Kel F is its usefulness at high temperatures up to 150°C, together with its lower cost and easier fabrication than P.T.F.E. (P.C.T.F.E. is readily moulded), which may make further work worth while. The characteristics of the material are given in the table of dielectric properties on p. 31. In the U.S.A., film has been made which, at 1 Mc/s, gives a peak power factor of 0·05 at 112°C, decreasing to 0·015 at 200°C. The permittivity (at 1 Mc/s) varies from 2·32 at room temperature to 2·75 at 200°C. Metal-coated Kel F sheets are being made by several companies in America, but sufficient experience has yet to be obtained in this country. Probably P.T.F.E., which is now being manufactured by Imperial Chemical Industries Ltd., will prove to be of more value as a high-temperature capacitor dielectric.

Polyethylene Terephthalate (Melinex or Terylene)

Melinex, a polyester material (known as "Mylar" in the U.S.A.) makes an excellent dielectric comparable with paper, but having the advantage of higher working temperatures (of the order of 130°C).

Table 7.2

Temperature (°C)	At 60 c/s		At 1 kc/s		At 1 Mc/s	
	Permittivity	Power factor (%)	Permittivity	Power factor (%)	Permittivity	Power factor (%)
0	3·02	0·5	2·99	0·8	2·79	1·6
25	3·02	0·21	3·01	0·47	2·83	1·9
75	3·02	0·14	2·99	0·12	2·95	1·7
100	3·08	0·69	3·06	0·46	3·01	1·4
125	3·36	1·20	3·29	1·40	3·15	1·7
150	3·46	0·64	3·45	0·68	3·31	2·0

Characteristics of the material are given in the dielectric properties chart (pp. 30–31), and full information on the variation of losses with temperature and frequency are given in a paper by Dr. Wilson Reddish in 1950 (*see* Bibliography, p. 253).

Melinex film can be used alone or interleaved with paper. When used alone it is usual to impregnate the film with polystyrene, mineral oil, etc., to fill pinholes. It is made in the United Kingdom in a thickness of 6μm; other thicknesses may soon be available. It is possible to metallize the material by silvering, or by vacuum metallizing with

aluminium, and other methods are possible. The use of a single film is an advantage over conventional impregnated-paper capacitors, where several tissues may be used, and compares with metallized-paper techniques.

The dielectric strength is a function of the film thickness and whilst

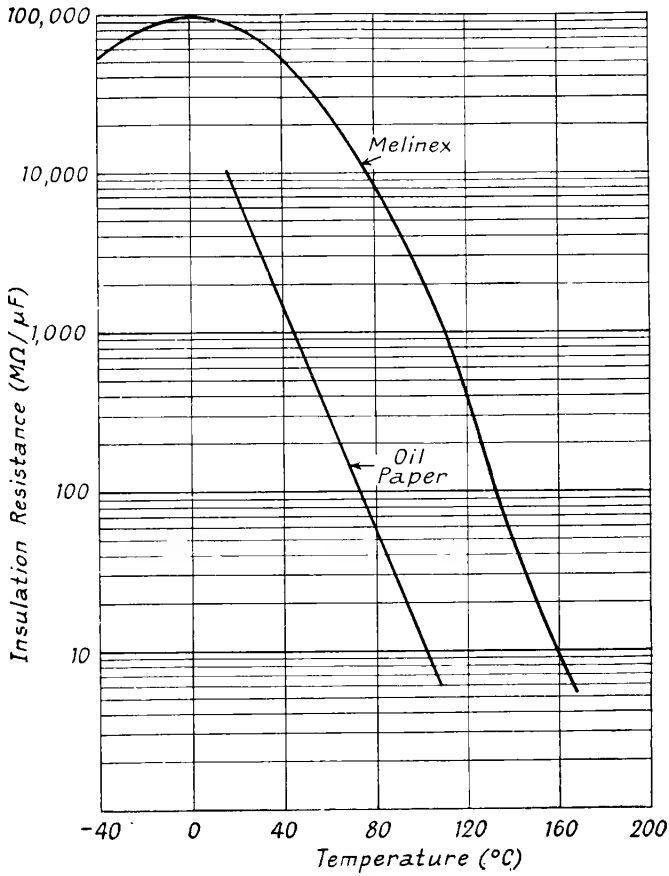


FIG. 7.5. INSULATION-RESISTANCE/TEMPERATURE CURVES FOR PAPER AND MELINEX FILM AT HIGH TEMPERATURES

in normally used thicknesses it is good, it becomes very good indeed when the film is over 0·005 in. thick. A film 0·007 in. thick will withstand an instantaneous voltage equivalent to 2,800 V/mil. In order to make full use of this property it is essential to prevent a.c. corona, as this damages the dielectric. It has been found that the film is

attacked to some extent in air by corona at 300 to 400 V r.m.s. Therefore, when high-voltage capacitors are used they should be effectively sealed and perfectly impregnated to prevent internal corona.

It is important to remember that the material is temperature and frequency sensitive. At low frequencies the permittivity is comparable with that of paper but at high frequencies it becomes comparable with that of polystyrene. At the change-over frequency the losses are

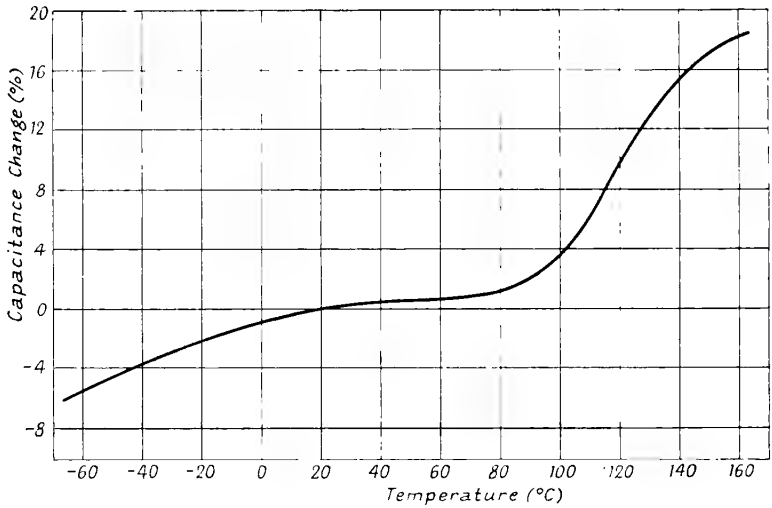


FIG. 7.6. CAPACITANCE VARIATION WITH TEMPERATURE FOR MELINEX CAPACITOR

higher and at room temperature this frequency occurs near 1 Mc/s. The variations of permittivity and loss or power factor with temperature are shown in Table 7.2 (p. 158).

One of the most important properties of Melinex is its extremely high insulation resistance at high temperatures as compared with paper. This is shown in Fig. 7.5.

The variation in capacitance of a typical Melinex capacitor over a temperature range from -60°C to $+160^{\circ}$C is shown in Fig. 7.6, and the change of power factor with temperature and with frequency is illustrated in Fig. 7.7.

IRRADIATED POLYTHENE

It is possible to increase the upper temperature limit of polythene without greatly affecting its electrical properties by exposing it to beta or gamma radiation. Polythene possesses very low losses at all radio

frequencies and a low permittivity, but it is softened at about 70°C (depending to some extent on its composition) and melts around 120°C. It is attacked and swollen by many organic solvents and hydrocarbon

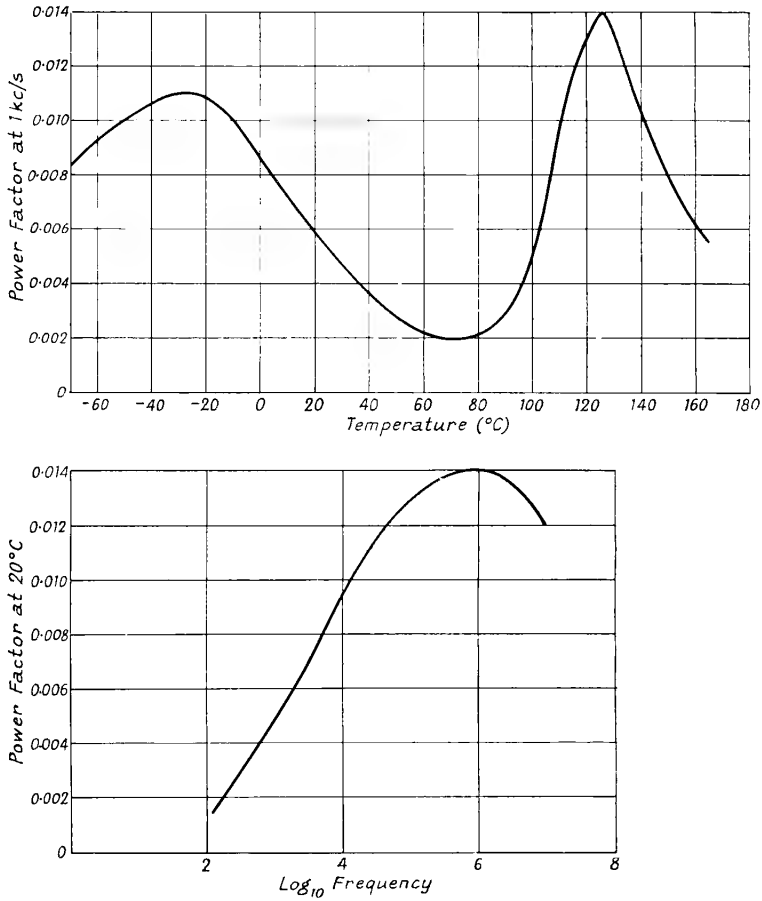


FIG. 7.7. VARIATION OF POWER FACTOR WITH TEMPERATURE AND FREQUENCY FOR MELINEX CAPACITOR

oils. When the polymer is submitted to gamma radiation from an atomic pile all these properties are modified to a degree dependent on the dosage. Mild dosage produces slightly greater heat resistance through some cross-linking mechanism, but increasing the dose renders the material more amorphous than crystalline, so that it does not soften or melt until temperatures of over 200°C are reached. At

the same time the dielectric properties are slightly degraded and the polythene is discoloured from opaque white to yellow. In this condition it is not attacked by solvents and oils. This change is thought to occur when the molecular chains of the polymer are cross-linked to a greater or lesser degree, according to the dosage, and hydrogen is liberated and partial oxidation takes place. Experiments are proceeding to introduce this material into capacitors, but difficulties are experienced in producing a finished capacitor, as it is not possible with present techniques to irradiate, at reasonable cost, enough film for winding as a capacitor. It is also not possible to irradiate the assembled capacitor, as the aluminium foil would absorb radiation. It is, however, possible to irradiate larger samples than those which can be accommodated in the Harwell pile by using linear accelerators such as those developed for medical purposes. These high-energy accelerators produce electron beams which can readily be directed on to the dielectric, and a similar effect is produced.

CAPACITORS WITH LOADED- OR FILLED-PLASTIC DIELECTRICS

Titania-loaded Polystyrene

Attempts have been made to increase the permittivity of polystyrene dielectrics by loading or filling them with ceramic powder of higher permittivity (usually titania). If the polystyrene is loaded with an equal volume of titania with a permittivity of 100 the mixed body has a permittivity of about 15; if it is loaded to three-quarters of its volume, the permittivity is about 30. At these high loadings, however, the material becomes brittle and difficult to roll into film or to fabricate into plates. A theoretical disadvantage is that discontinuity of fields within the mixture would result in breakdown under voltage stress at voltages lower than the breakdown voltages of the materials themselves. Difficulties are also experienced with moisture absorption—it is necessary to dry out the ceramic powder before loading and the effects of heating titania to these temperatures are uncertain. If a very thin film is required (of the order of 0·002 in.) the particle size of titania or other powder is likely to be of the same order, which may lead to mechanical and electrical weaknesses. Experimental films of polystyrene loaded with titania have been produced in thicknesses down to 0·003 in. with permittivities of the order of 25 and with power factors of the order of 2 per cent.

CHAPTER 8

ELECTROLYTIC CAPACITORS

IT is nearly seventy years since the first electrolytic capacitor was made in Germany and nearly ninety years since the principle was first noticed. The outstanding advantage of the electrolytic capacitor is its large capacitance/volume ratio.

PLAIN-FOIL TYPES

The large capacitance arises from the very thin film of dielectric used—of the order of 10^{-5} cm (a few millionths of an inch). The method of

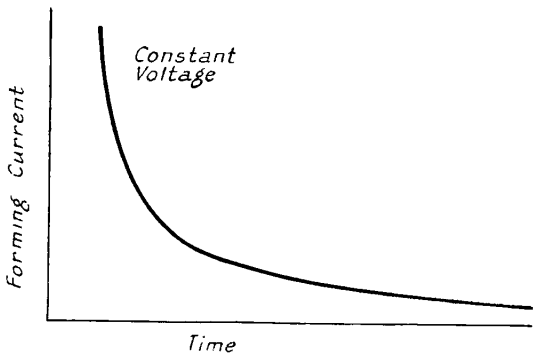


FIG. 8.1. FORMING CURRENT FOR CONSTANT VOLTAGE FOR AN ELECTROLYTIC CAPACITOR

making this thin film is by anodic oxidation. Certain metals, notably aluminium, tantalum, vanadium, magnesium, bismuth and antimony, are readily coated with a film of dielectric by an electrolytic "forming" process. If an aluminium electrode is placed in a solution of ammonium borate and a constant voltage applied the initial current will be high, but it will drop gradually as the dielectric film forms, as shown in Fig. 8.1.

The forming process consists in the deposition of a thin film of aluminium oxide on the surface of the plate. In modern practice, the anode foil enters a tank of electrolyte with a constant voltage applied and passes through the tank until the required thickness of film is produced.

The film is extremely strong. A p.d. of 100 V across a film of 10^{-5} cm represents a dielectric strength of ten million volts per centimetre. This is beginning to approach the theoretical strength predicted by the ionic

theory of crystals, which strength has never otherwise been approached in practice. The maximum capacitance obtainable with a given anode surface area is inversely proportional to the voltage used in the forming process—i.e. the film thickness depends on the forming voltage. Low-voltage capacitors have thinner films and, therefore, a higher capacitance/volume ratio than have high-voltage capacitors. Since the working voltage is about 90 per cent of the forming voltage and the thickest film is formed at about 600 V, a limit of 500 to 550 V (at room temperature) is set as the maximum working voltage obtainable. Ripple voltage must be included in this figure if the capacitor is being used for rectifier smoothing. It can also be seen that the surge voltage is limited in this type of capacitor. If the capacitor surge voltage is exceeded, scintillation will occur. This scintillation voltage is the sparking-voltage characteristic of the capacitor and represents partial breakdown of the dielectric, resulting in the formation of gaseous products, the production of local high temperatures and possibly actual carbonization of the separator materials.

The essential parts of an electrolytic capacitor and their functions are thus—

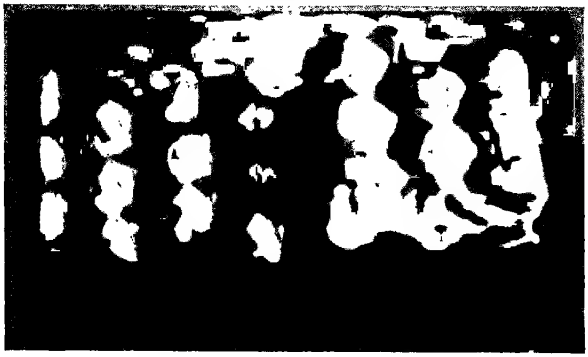
1. The aluminium foil . . .	Positive, or anode
2. The oxide film	Dielectric
3. The electrolyte (usually a paste of glycol and ammonium tetraborate)	Negative, or true cathode
4. Spacers	Necessary to separate the "cathode" and anode film from direct contact
5. A second aluminium foil . .	A contact electrode to the electrolyte: the "cathode"

Aluminium oxide films formed by anodization can be of two different types, namely porous or non-porous. The former, which are formed in electrolytes of strong acids such as sulphuric, chromic, phosphoric or oxalic acid, are not suitable for dielectrics in electrolytic capacitors; most of the anodization of aluminium anodes for capacitors is carried out in borate electrolytes. Porous and non-porous alumina films have a cellular structure, and by optical and electron microscopy it has been found that this is most pronounced in films formed at room temperature and below, and approaches that shown in Fig. 8.2.

Both surfaces of the oxide film are covered with domes, and the metal surface is correspondingly covered with craters. By chemical treatment it is found that the oxide in the centres of the cellular units is of different composition from that in the walls.

As the anodic alumina film grows, the size of the cellular units

increases so as to maintain a fixed relationship between the thickness of the oxide and the diameter of the cells. At all times the units are close packed in the oxide coating, and so they can only expand if their



Plessey Co., Ltd.

FIG. 8.2. IDEALIZED STRUCTURE OF ANODIC ALUMINIUM OXIDE

number decreases correspondingly. The number of cells (N) and their diameter (D) are related by the formula $ND^2 = \text{constant}$. As the diameter is proportional to the formation voltage, provided the oxide

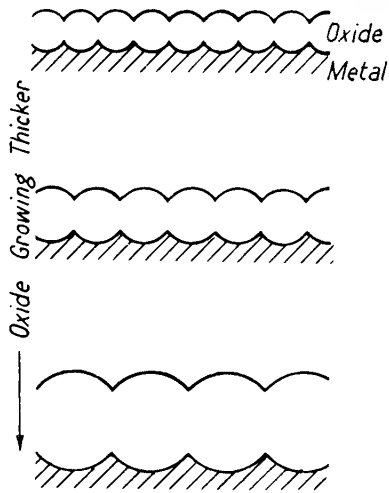


FIG. 8.3

has reached its equilibrium thickness, this formula can be written as $NV^2 = \text{constant}$. Various stages in the growth of the oxide film are shown in Fig. 8.3.

There are two ways in which the number of cellular units can decrease, i.e. either by coalescence of neighbours or by submersion following more rapid growth of other units.

A plain-foil dry electrolytic capacitor is made by first forming the

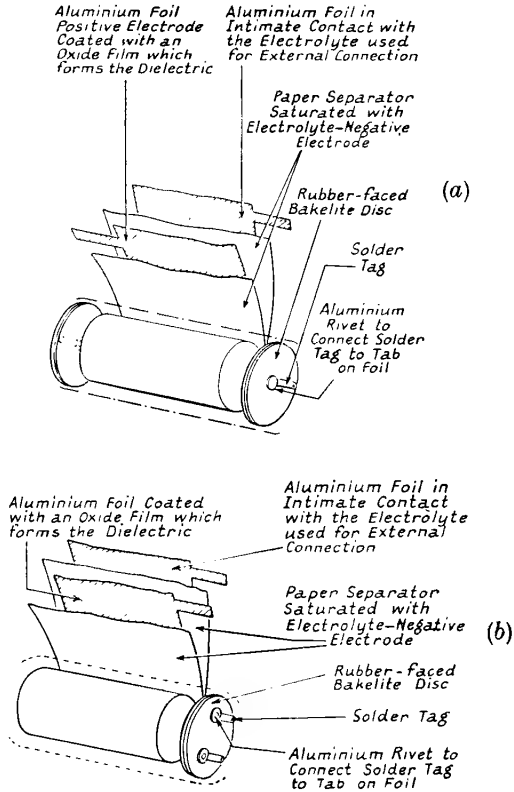

Aluminium Foil Positive Electrode Coated with an Oxide Film which forms the Dielectric
Aluminium Foil in Intimate Contact with the Electrolyte used for External Connection
Paper Separator Saturated with Electrolyte-Negative Electrode
Rubber-faced Bakelite Disc
Solder Tag
Aluminium Rivet to Connect Solder Tag to Tab on Foil
(a)
Aluminium Foil Coated with an Oxide Film which forms the Dielectric
Aluminium Foil in Intimate Contact with the Electrolyte used for External Connection
Paper Separator Saturated with Electrolyte-Negative Electrode
Rubber-faced Bakelite Disc
Solder Tag
Aluminium Rivet to Connect Solder Tag to Tab on Foil
(b)

FIG. 8.4. CONSTRUCTION OF PLAIN-FOIL DRY ELECTROLYTIC CAPACITORS

(*a*) Double ended (*b*) Single ended

coating of aluminium oxide on both sides of an aluminium foil about 0·002 in. thick. Two strips of aluminium foil are used (the formed foil as the anode and the plain foil as the contacting electrode for the electrolyte cathode), separated by two layers of porous paper soaked with electrolyte. This assembly is rolled up, the ends are closed with wax and then sealed into an aluminium container as shown in Fig. 8.4.

The corrosive effects of heat and moisture are counteracted by making an effective seal for the container and using aluminium for all metal parts. As long as the electrolyte is prevented from seeping out and coming into contact with some other metal, no corrosion will take place. An effective seal also delays the electrolyte in drying out and so greatly shortening the life of the capacitor.

During the last few years considerable experimental work has been undertaken to obtain greater surface area on the anodes and on the use of new anode materials and new electrolytes. It has been known for some time that an increase in the purity of the aluminium foil used

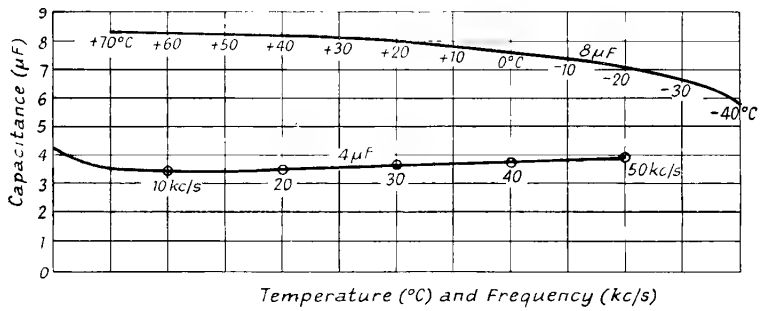


FIG. 8.5. VARIATION OF CAPACITANCE WITH TEMPERATURE AND FREQUENCY FOR ELECTROLYTIC CAPACITORS

would lengthen the life of the capacitor, but the effect of the various impurities present in the metal has yet to be fully investigated.

Reversible electrolytic capacitors are also made, by pre-forming both the aluminium foils and bringing out separate contacts. Each film is effective during the half-cycle when the other is ineffective.

ELECTRICAL CHARACTERISTICS

The principal characteristics to be considered are

(1) Capacitance and the effect of temperature and frequency.
(2) Power factor and the effect of temperature and frequency.
(3) Leakage current and the effect of time, temperature and voltage.

Taking a typical capacitor, Fig. 8.5 shows the variation in capacitance due to temperature and frequency. It can be seen from the upper curve that electrolytic capacitors lose a great deal of their effectiveness at low temperatures. This is due to the freezing of the electrolyte and consequent increase in series resistance.

The lower curve shows the variation of capacitance with frequency.

From zero to 10 kc/s the capacitance decreases slightly; the equivalent series resistance, after falling rapidly up to 500 c/s, decreases more slowly up to 10 kc/s. The power factor increases from a low value to 50 per cent through the same range. Above 10 kc/s the capacitance increases slightly but does not rise more than 10 per cent at 50 kc/s.

Electrolytic capacitors can be used as smoothing capacitors at these frequencies to ensure a d.c. supply, the a.c. energy being dissipated. At radio frequencies they provide a low-resistance path of approximately

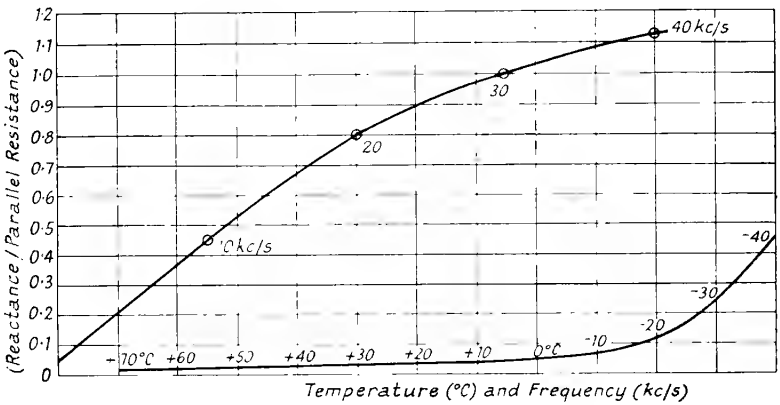


FIG. 8.6. VARIATION OF POWER FACTOR (RATIO OF REACTANCE TO PARALLEL RESISTANCE) WITH TEMPERATURE AND FREQUENCY FOR ELECTROLYTIC CAPACITORS

1 Ω at room temperature. They can therefore be used with tuned circuits, provided that a loss of this order can be tolerated.

Fig. 8.6 shows the effect on power factor of variations in temperature and frequency. The high power factor of electrolytic capacitors is due to the resistance of the electrolyte, the equivalent series resistance of an electrolytic capacitor being very little greater than the resistance of the electrolyte. This high power factor is inevitable—any attempt to reduce the resistance of the electrolyte by using a thinner separator would lead to increased leakage current, lower breakdown voltage and shortened life. On the other hand, the power factor must not be made any higher (even if a high power factor can be tolerated at normal temperature) because the corresponding value at low temperatures would be excessive.

At − 30°C, an increase in value of the power factor of ten times that at + 20°C is quite normal. It is fortunate that the power factor increases towards the lower end of the temperature range, since the worst effect of the high power factor is the heat produced in the capacitor

itself, and an important feature is the continued decrease of power factor with increase of temperature, which ensures safe working. If the power factor were to increase with temperature faster than the rate of cooling, an unstable condition would be reached and the capacitor would eventually blow up.

Since power factor $= R/Z = R\omega C$, approximately, the decrease of capacitance at low temperature tends to keep the power factor down. The series resistance R must, therefore, increase more quickly than the power factor at low temperatures. Thus, if the capacitance is halved and the power factor increases to ten times its value, the equivalent

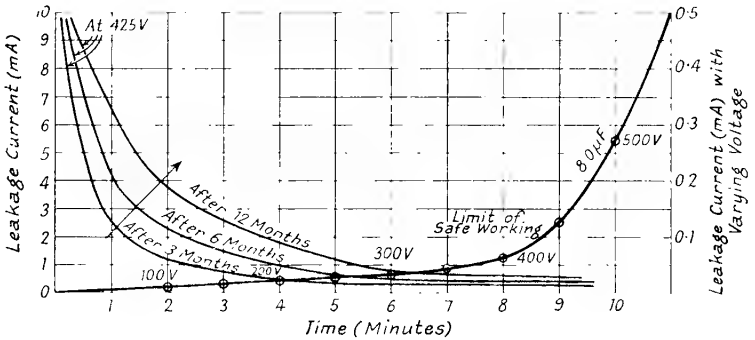


FIG. 8.7. VARIATION OF LEAKAGE CURRENT WITH TIME AND APPLIED VOLTAGE FOR ELECTROLYTIC CAPACITORS

series resistance must have increased to twenty times its value, about 100 Ω for a typical 1-μF capacitor at 20°C.

The safe working voltage of the capacitor is determined by the leakage-current/voltage characteristics, as shown in Fig. 8.7. In the example the limit of safe working occurs at about 400 to 450 V. The leakage current rises rapidly above this voltage region and breakdown soon sets in.

The leakage current also increases with increase of temperature and becomes very large as breakdown is approached. The leakage-current/temperature curve is similar in shape to the leakage-current/voltage curve.

During shelf life, both curves become shallower in the direction shown by the arrow on the leakage-current/voltage curves, the reverse process taking place in operation. It is mainly this upward drift of the leakage-current/time curve (with the simultaneous effect on the leakage-current/voltage curve) which is responsible for the failure of the old type of electrolytic capacitors after a long period of storage.

In general, the disadvantages of electrolytic capacitors may be

summarized as the high power factor (about ten times that of an average paper capacitor), the variation in capacitance (capacitance variations from — 20 per cent to + 50 per cent of the nominal value are possible), the small safety factor, and the high leakage current.

The great advantages of electrolytic capacitors are, of course, their very high capacitance/volume ratio and their reasonably low cost. For

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FIG. 8.8. ELECTRON MICROGRAPH OF ETCHED ALUMINIUM FOIL
× 10,000

smoothing, decoupling and by-pass purposes these advantages may outweigh all the disadvantages.

The following general conditions should be satisfied whenever an electrolytic capacitor is used.

(1) The peak voltage applied should be less than the rated voltage. When an a.c. ripple is superimposed on d.c., the peak voltage is equal to the d.c. plus the peak of the a.c. The a.c. ripple should not normally exceed 10 per cent of the d.c. voltage.

(2) The applied voltage should never be reversed. The d.c. should always be in the correct polarity, but a small alternating voltage may be applied for a few minutes without any polarizing voltage. It is, in fact, convenient to do this when measuring the impedance.

(3) The ripple current should not produce overheating. The maximum ripple current allowed for each size of capacitor is usually given.

A requirement often met in transistor circuitry is that the electrolytic capacitor shall have a low impedance at, say, 10 kc/s or even higher frequencies. This high-frequency performance can be achieved only by careful design and by the choice of materials so as to obtain low inductance and low internal series resistance.

Another aspect of high-frequency performance is the behaviour of

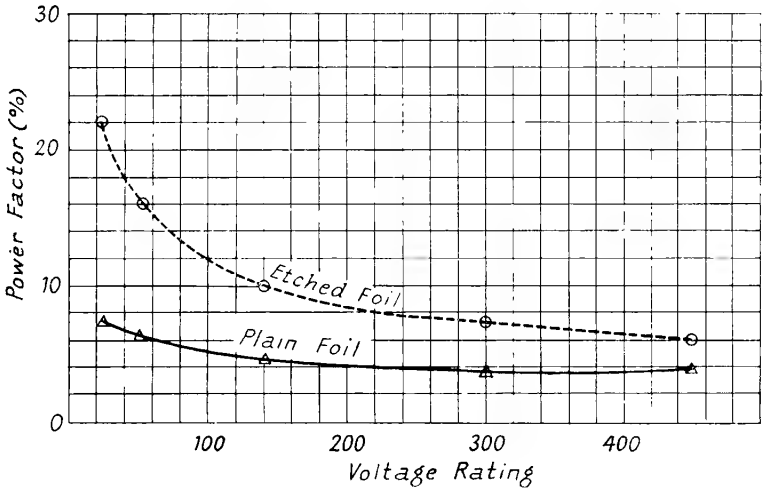


FIG. 8.9. VARIATION OF POWER FACTOR WITH VOLTAGE FOR PLAIN- AND ETCHED-FOIL ELECTROLYTIC CAPACITORS

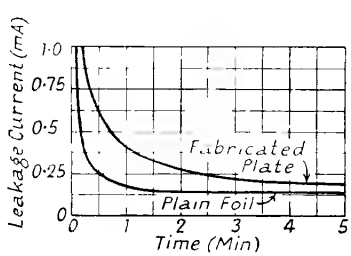
the capacitor under discharge current pulses of 1 μs duration, as met within transistor computers. In this application it is again necessary that the capacitor should have a low internal series resistance and that during the discharge pulse the internal resistance calculated from the voltage drop across the capacitor should be no more than, say, 0·2 Ω.

ETCHED-FOIL TYPES

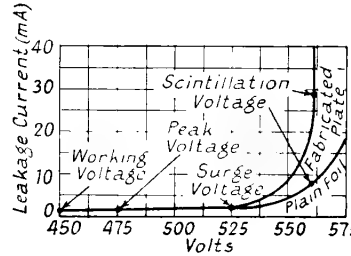
The etched-foil type is similar in construction to the plain-foil type, but the anode foil is mildly acid etched before forming with a consequent increase in the anode surface area. This is shown clearly in the electron micrograph of Fig. 8.8. As the electrolyte is a paste it is able to make contact with the whole of the thin oxide film that is formed on this undulating surface. It is essential to control the etching process closely so that "thin" spots are not left on the foil and also to ensure that no acid is left which might contaminate the foil.

The increase in surface area results in a considerable increase in the

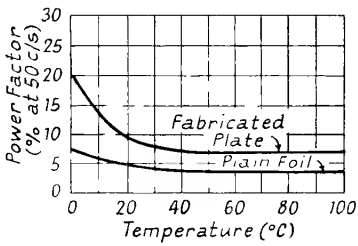
capacitance obtainable. The polarization capacitance of a plain aluminium plate is about 16 μF/in.^{2}, whilst a foil etched to its maximum ratio and in a glycol/boric-acid electrolyte gives 125 μF/in.^{2} The effective capacitance gain is therefore between 7 and 8 times. The power factor is increased by a factor of from 2 to 4; Fig. 8.9 shows



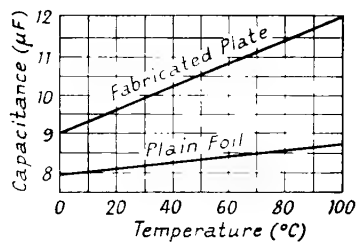
Leakage/Time Curves of Typical 8μF, 450V, Plain-foil and Fabricated-plate Capacitors



Leakage/Voltage Curves of Typical 8μF, 450V Plain-foil and Fabricated-plate Capacitors



Power Factor/Temperature Curves of Typical 8μF, 450V, Plain-foil and Fabricated-plate Capacitors



Capacitance/Temperature Curves of Typical 8μF, 450V, Plain-foil and Fabricated-plate Capacitors

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FIG. 8.10. CHARACTERISTICS OF PLAIN-FOIL AND FABRICATED-PLATE 8-μF 450-V, ELECTROLYTIC CAPACITORS

the variation of power factor with voltage rating at 25°C and 120 c/s for plain- and etched-foil dry electrolytic capacitors.

SPRAYED-GAUZE OR FABRICATED-PLATE TYPES

The sprayed-gauze anode consists of a fine aluminium gauze on which is sprayed pure aluminium from a metal-spraying pistol. The effective area is still further increased by this method and up to twelve times the capacitance of an equivalent plain-foil electrode can be obtained. A comparison between the characteristics of the sprayed-gauze or fabricated-plate type and the plain-foil type is shown in Fig. 8.10.

TANTALUM ELECTROLYTIC CAPACITORS

There are three main types of electrolytic capacitor using tantalum: tantalum porous pellet or liquid-electrolyte sintered-anode type, tantalum foil, and solid-electrolyte tantalum types.

The starting-point for all three types of tantalum capacitors is finely powdered tantalum having a purity of the order of 99·7 per cent. In the compacted porous-anode type, the powder is formed into the shape of the anode, directly on a tantalum wire assembly, and sintered.

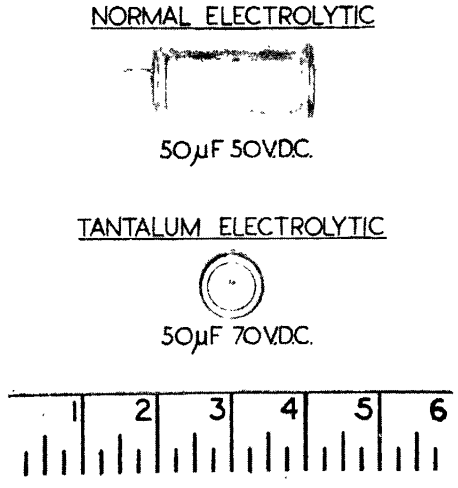

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FIG. 8.11. COMPARATIVE SIZES OF TANTALUM AND NORMAL ELECTROLYTIC CAPACITORS

Tantalum foil and wire are made from ingots formed by alternately sintering and forging powder compacts until the desired density is obtained. The ingots are rolled into sheets and then into foil, or rolled and drawn into wire.

Because capacitance is a function of surface area of the tantalum and its oxide film, it is desirable to use as fine a powder as is practicable. On the other hand, porous anodes of consistent quality are difficult to produce with very fine powder, of the order of 15-μms diameter or smaller. Addition of a coarser powder gives a mixture that is less sensitive to variations in processing conditions.

Sintering takes place in a vacuum at the temperature of 2,040°C. The vacuum is necessary because of the extreme reactivity of tantalum

with all common gases at elevated temperatures. Sintering performs the functions of welding the tantalum powder into a structurally strong porous mass and removing most of the small quantities of impurities such as carbon, silicon and gases, and all of the electrolysis salts normally present in the powder. After sintering, the compacts are electrolytically oxidized to form the dielectric surface film.

Tantalum-pellet Electrolytic Capacitors

The comparative sizes of a normal electrolytic capacitor and a sintered-tantalum-pellet electrolytic capacitor of similar capacitance

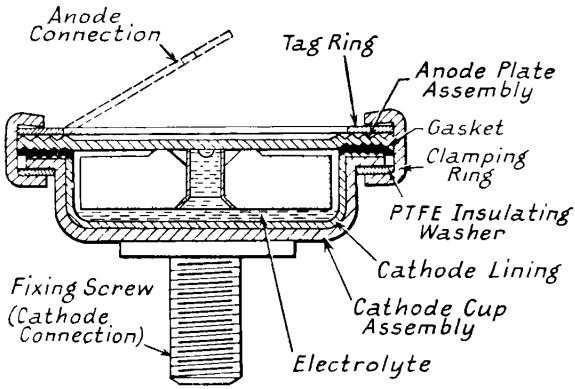

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Fig. 8.12. Construction of Tantalum-pellet Electrolytic Capacitor

may be seen in Fig. 8.11. The tantalum-pellet capacitor is made by sintering a capsule of pressed powdered tantalum in a vacuum and then mounting it inside a silver cup containing sulphuric acid as the electrolyte. These capacitors are therefore essentially "wet" electrolytic capacitors. The tantalum is the anode and the silver cup the cathode. The unit is sealed by pressing cathode and anode together over a ring of polytetrafluoroethylene (P.T.F.E.), which serves as an insulating washer. P.T.F.E. is necessary if advantage is to be taken of the very wide working temperature range of the capacitor. The detailed construction of the unit is shown in Fig. 8.12.

The variations of capacitance and power factor with temperature are shown in Fig. 8.13, and the d.c. leakage with time, voltage and temperature is shown in Fig. 8.14.

It is possible to use the tantalum-pellet capacitor as a circuit element, as the leakage current is not appreciable below about 85°C and at ordinary temperatures it is very small indeed, being comparable with

that in a good-quality paper capacitor of the same capacitance and of vastly greater size.

The low leakage and very stable capacitance characteristics enable these capacitors to be used as timing elements in very-long-period discharge circuits, and sometimes they have advantages over conventional components for this purpose. Such conditions are found, for instance, when compact circuits are required to work in a damp atmosphere. In this instance, the capacitance values must be kept high

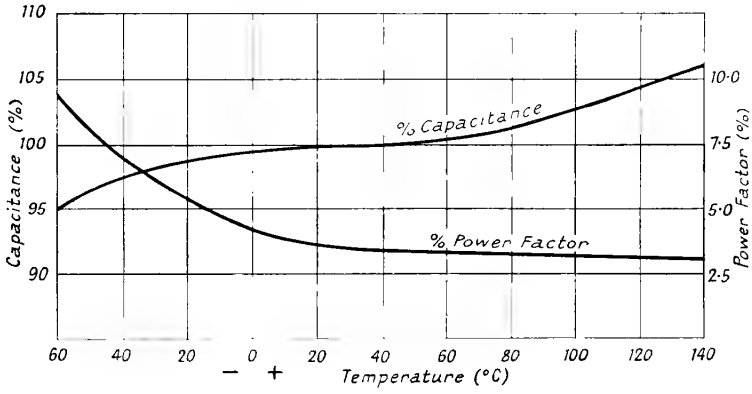

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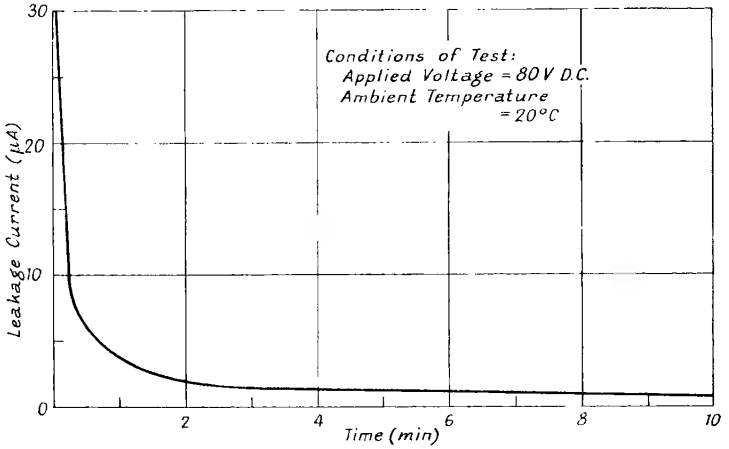
FIG. 8.13. VARIATION OF CAPACITANCE AND POWER FACTOR WITH TEMPERATURE FOR 55-μF TANTALUM ELECTROLYTIC CAPACITOR, AT 70 V D.C. AND 50 C/S

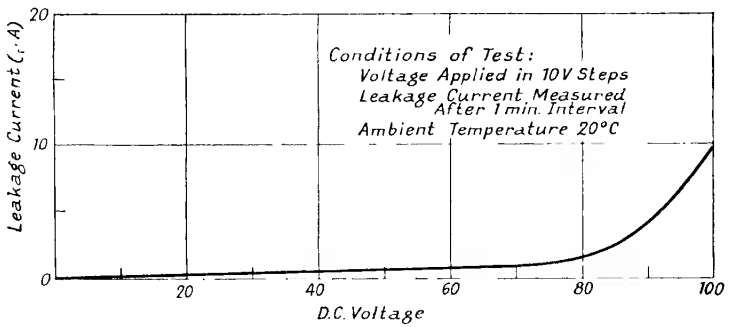
so that the resistances will remain reasonably low and not be affected by leakage to earth. The large size of ordinary good-quality capacitors, having a capacitance of only a few microfarads, entirely precludes their use in such circuits.

The electrical characteristics of a polarized electrolytic capacitor, important in the use of such a capacitor as a circuit element, are—

Capacitance	55 μF, approx.
Temperature coefficient	500 ppm/°C, approx.
Leakage current at 70 V and room temperature	$< 1\,\mu$A
Maximum working voltage up to 125°C . .	70 V

These data show that the resistance is about 70 MΩ or more, and time constants of the order of 3,500 sec, or approximately 1 hr, may be realized by the discharge of these capacitors through a suitable high external resistance. In practice, a slight re-forming always occurs under an applied voltage, so that while on first applying the voltage the discharge is rather faster than is suggested by these figures, even higher resistances (and associated time-constants) are obtained on





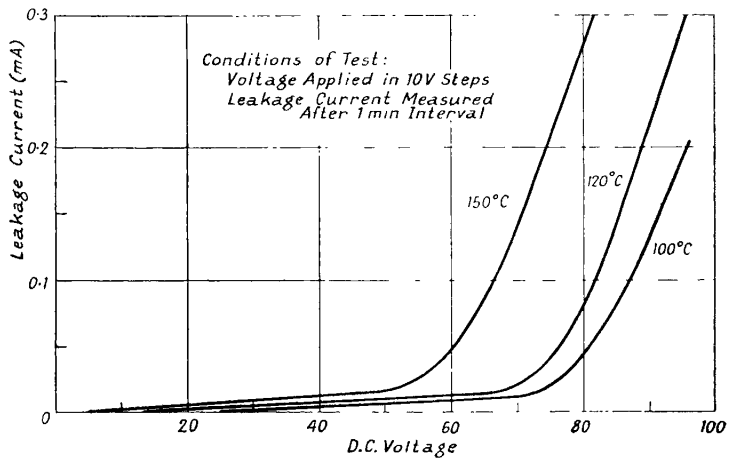


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FIG. 8.14. VARIATION OF LEAKAGE CURRENT WITH TIME,

prolonged running. This re-forming, except perhaps for capacitors which have been in store for a long time, does not take more than a few seconds, and after this a uniform, almost exponential, discharge is obtained.

This behaviour is illustrated in Fig. 8.15, showing the discharge of a tantalum capacitor through a 90-MΩ resistance-chain, as measured on a sensitive galvanometer.

The initial forming period is approximately 15 sec, during which

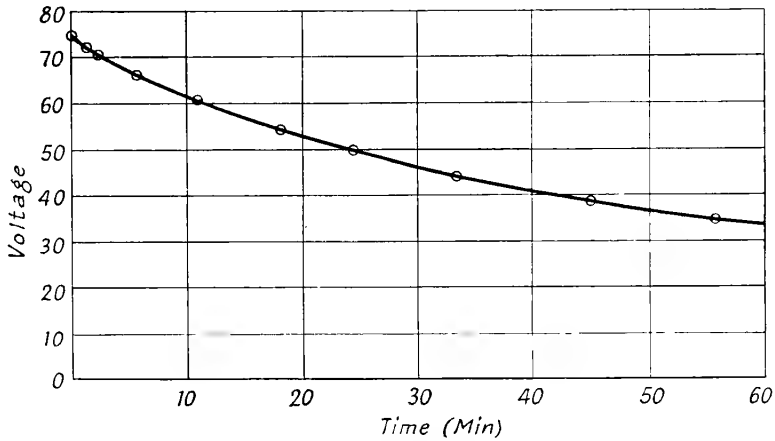

FIG. 8.15. DISCHARGE OF TANTALUM CAPACITOR THROUGH RESISTANCE OF 90 MΩ

time the necessary connections and adjustments are made—thereafter the current falls to half its initial value in approximately 50 min.

Comparing this with the theoretical half-value period ($= 0{\cdot}7RC$) of approximately 1 hr, it is clear that the effect of leakage is practically negligible in a 100-MΩ circuit, and that the internal resistance must have values even higher than are suggested by the data.

Even through a much lower resistance the discharge is very slow; the capacitor has been used in a multivibrator of very low recurrence frequency in which a recurrence period of approximately 2·5 min can be obtained, using a charging resistance of only 1 MΩ. A longer period—up to 12 min—can be obtained with a larger resistance, but beyond this there will be difficulty arising from grid current in the second pentode valve.

For very long time-constants the effective capacitance of a capacitor can be greatly increased by using a Miller integrating circuit, the unit being connected between the grid and anode of a valve fed through a suitable resistance. This will work only if the leakage is low enough not to sweep the valve off its grid-base. Unless the anode voltage is

excessive the tantalum capacitor can be so used, and owing to its large capacitance the resistances in the circuit can all be kept low. Using a load of only 10 kΩ and a charging resistance of 100 kΩ a run-down time of approximately 3 min can be obtained. No tests have been made of the maximum run-down period which can be obtained in this way, but it may be noted that the forming voltage, which helps to ensure good results, is automatically present in such circuits.

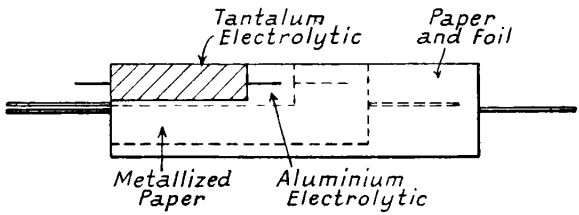

FIG. 8.16. SIZE OF TANTALUM-FOIL CAPACITOR COMPARED WITH OTHER TUBULAR TYPES

TANTALUM-FOIL ELECTROLYTIC CAPACITORS

The main advantage of tantalum-foil electrolytic capacitors is their small size due to the dielectric constant of 22·0 of the anodic film, and as they are best suited to low-voltage operation at present and are limited in their high-temperature operation they are eminently suitable for use with transistors. They are also very reliable.

The size of a typical tantalum-foil capacitor, compared with the sizes of capacitors having other dielectrics (for 100 V working in each case), is shown in Fig. 8.16.

These capacitors are similar in construction to an aluminium electrolytic capacitor but tantalum metal foil is used for the electrodes. Tantalum is an inert metal and resists attack by most acids, so that no galvanic corrosion can occur when it is used with an electrolyte. The spacing tissue is usually low-density rag-base paper, impregnated with electrolyte; practically no gas is liberated, so that it is possible to seal the capacitor completely. Tantalum electrolytic capacitors do not need re-forming and possess long storage lives. They are made as polarized types and as non-polarized types; typical capacitances which can be obtained for polarized types in a can length of 1·6 in. and diameter 0·34 in. are 200 μF at 6 V or 10 μF at 150 V. Tolerances are approximately ± 20 per cent above 0·25 μF and slightly more below this value. The power factor varies considerably with temperature and also with voltage rating. Typical figures at 50 c/s are 12 per cent at + 70°C, 8 per cent at room temperature and 20 per cent at − 40°C for 25 V and above. The power factor increases with decrease of working voltage. The maximum operating temperature is about 125°C.

The most interesting characteristic is the extremely low leakage current, which for a 1 μF, 150 V, capacitor at 20°C is about 10 μA after 10 sec, dropping to 0·7 μA after 1 hr and 0·5 μA after 3 hr. The

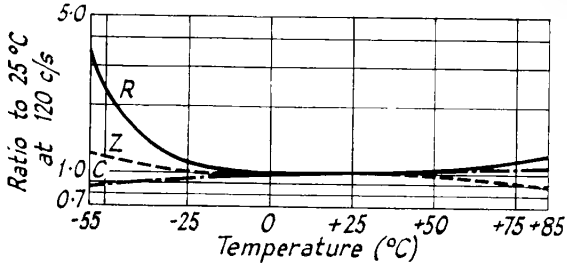

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FIG. 8.17. TYPICAL CURVES OF IMPEDANCE, CAPACITANCE, AND EQUIVALENT SERIES RESISTANCE WITH TEMPERATURE FOR 6-V PLAIN-FOIL CAPACITORS

C. Capacitance
R. Equivalent series resistance
Z. Impedance

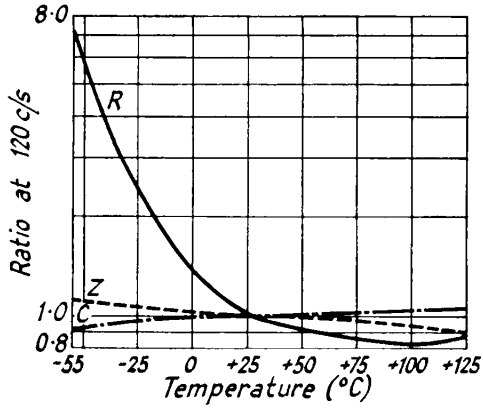

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FIG. 8.18. TYPICAL CURVES OF IMPEDANCE, CAPACITANCE AND EQUIVALENT SERIES RESISTANCE WITH TEMPERATURE FOR 36-μF 100-V POLARIZED ETCHED-FOIL CAPACITORS

C. Capacitance
R. Equivalent series resistance
Z. Impedance

time constant is therefore given by

$$RC = (E/I)C = 150/0{\cdot}7 \times 1 \simeq 200\ \Omega\text{-F (or sec)}$$

As in the case of aluminium foil, etching can be used to increase the surface area. Typical curves of impedance, capacitance and equivalent series resistance for plain- and etched-foil types are shown in Figs. 8.17 and 8.18.

Tantalum-foil electrolytics can be used as decoupling capacitors, but should not be used in a.c. power circuits, because there is little voltage safety factor available when they are used back-to-back. When used

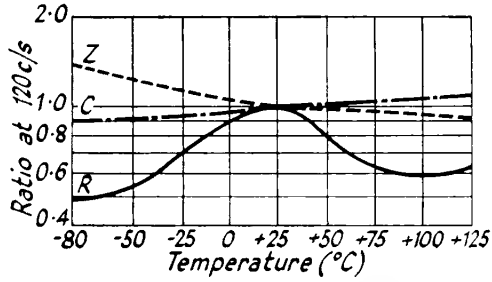

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FIG. 8.19. TYPICAL CURVES OF IMPEDANCE, CAPACITANCE AND EQUIVALENT SERIES RESISTANCE WITH TEMPERATURE FOR 47-μF 35-V SOLID-TANTALUM CAPACITORS

C. Capacitance
R. Equivalent series resistance
Z. Impedance

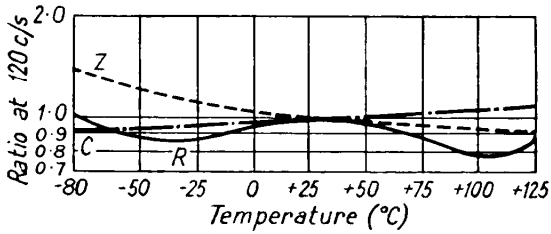

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FIG. 8.20. TYPICAL CURVES OF IMPEDANCE, CAPACITANCE AND EQUIVALENT SERIES RESISTANCE WITH TEMPERATURE FOR 68-μF 20-V SOLID-TANTALUM CAPACITORS

C. Capacitance
R. Equivalent series resistance
Z. Impedance

as coupling capacitors in timing circuits the pulse shape is likely to be distorted, i.e. the steep front is likely to deteriorate because of the phase changes introduced by the series resistance. When used at higher frequencies, losses begin to increase seriously at about 1 to 10 kc/s, compared with the pellet type, where losses begin to increase at a few hundred cycles per second. In both these types the losses are much more marked at temperatures below room temperature.

Solid-electrolyte Tantalum Capacitors

This type was first developed by the Bell Laboratories, U.S.A., in 1956 and uses a solid semiconductor in place of a liquid electrolyte. As in the sintered-porous-anode type, the pellets are pressed, sintered and electrochemically formed. After formation, however, the pellets are impregnated with an aqueous solution of a manganous salt. This salt is pyrolytically decomposed to form manganese dioxide, which is the working electrolyte in solid form. A carbon compound is applied over the external layer of MnO_2 to allow a metal cathode to be applied. The unit is then sealed into a metal case, or moulded in plastic.

The capacitance stability with temperature is extremely high, and Figs. 8.19 and 8.20 show impedance, capacitance and equivalent series resistance for two typical capacitors. It can be seen that the low-temperature performance of this type of capacitor is improved.

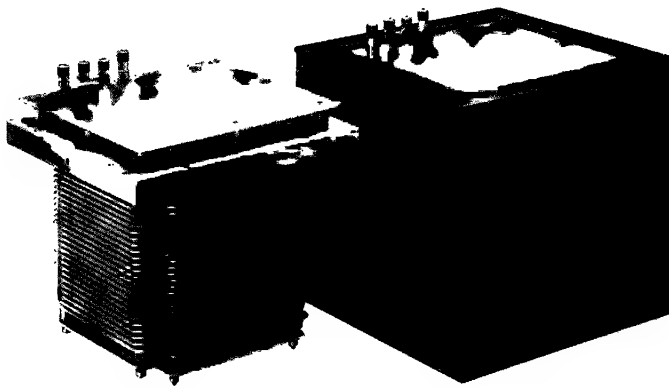
Solid tantalum capacitors charge immediately when voltage is applied, even after long periods of storage.

CHAPTER 9

AIR-DIELECTRIC, VACUUM AND GAS-FILLED CAPACITORS

AIR-DIELECTRIC TYPES

AIR-DIELECTRIC fixed capacitors are used mainly as laboratory standards of capacitance, particularly as high-voltage standards. They are either parallel-plate or concentric-cylinder types. In both types, great



H. W. Sullivan, Ltd.

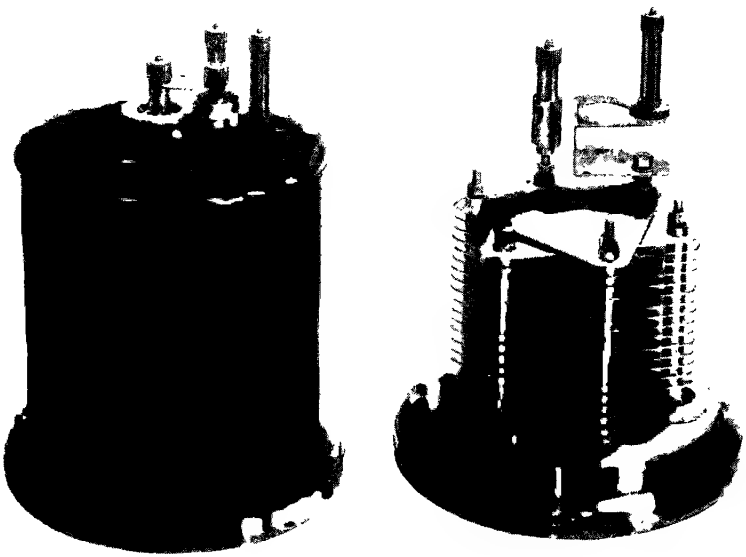
FIG. 9.1. CONSTRUCTION OF AIR-DIELECTRIC FIXED CAPACITOR

care is taken in obtaining and preserving dimensional stability. The parallel-plate types are similar in principle to the precision variable capacitors, but designed to function at one fixed capacitance; these plates are circular, square or triangular in shape. A typical construction of a standard fixed air-dielectric capacitor is shown in Fig. 9.1.

The insulating material used is fused silica and the whole capacitor is shielded in a metal case. Fixed-value air-capacitor standards are available from about 50 pF to about 10,000 pF. The accuracy of adjustment to a nominal value varies from 0·01 to 0·05 per cent, according to capacitance value and construction. For capacitors above 200 pF the accuracy to which actual values are reported is between 0·01 and

0·02 per cent. The probable permanence of value throughout a number of years varies between 0·01 per cent for the larger capacitance values and 0·04 per cent for the smaller values.

Miniature types are made, designed to have low residual inductance and conductor resistance, so that they can be used at higher radio frequencies. Such a capacitor is shown in Fig. 9.2.



H. W. Sullivan, Ltd.

FIG. 9.2. AIR-DIELECTRIC FIXED CAPACITOR WITH LOW RESIDUAL INDUCTANCE

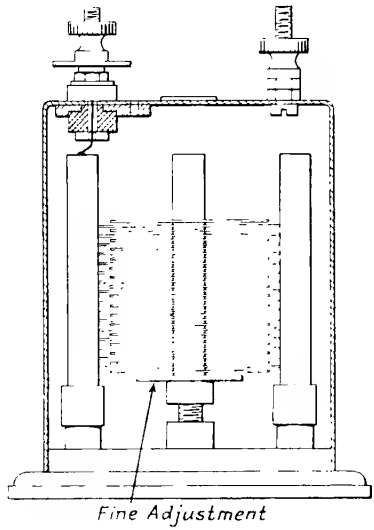
Both types are temperature compensated and the temperature coefficient of capacitance is usually less than 10 parts in 10^6 per degree centigrade.

An example of European manufacture is the range of fixed capacitors made by Messrs. Philips Ltd., Eindhoven, Holland, and the construction employed for these is shown in Fig. 9.3. Two sets of circular brass plates are interlaid horizontally. One set is soldered to two brass rods insulated from the brass base, the other set to two brass rods fixed to the base. The number of plates is determined by the capacitance required.

For calibration, a small circular brass plate on a screw thread is used, the plate being locked after final adjustment. For this type of fixed capacitor the maximum deviation from the nominal capacitance at 20°C is $\pm$ 0·15 per cent and the average temperature coefficient is

25×10^{-6} parts per degree centigrade. The maximum loss angle at 1 Mc/s (tan δ) is 0·0003, provided that the relative humidity of the air is not greater than 75 per cent. Standard capacitors of this type are made in many capacitance values, ranging from 10 pF to 1,000 pF.

The concentric-cylinder type is similar in principle to the vacuum capacitor described in the next section.



Philips Ltd., Eindhoven

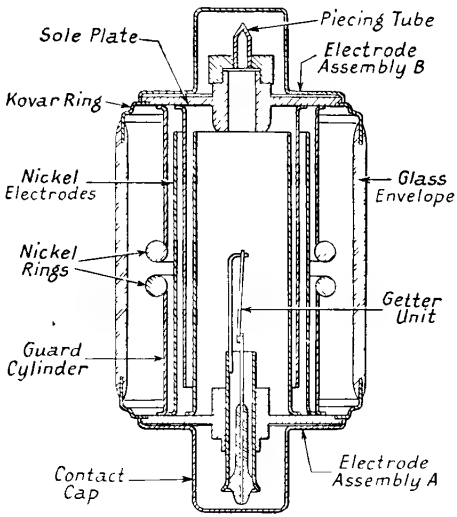
FIG. 9.3. CONSTRUCTION OF AIR-DIELECTRIC FIXED CAPACITOR

VACUUM CAPACITORS

The principle of using vacuum as a dielectric for capacitors is not new. Vacuum capacitors were developed originally in America but have since been developed and manufactured in Great Britain. Their main use is as transmitter capacitors in airborne radio equipments and as blocking and decoupling capacitors in large industrial and transmitting equipments. For airborne use the high internal breakdown voltage is achieved by using a hard vacuum. The operating voltage is then theoretically limited by the value of external breakdown voltage, which depends on the ambient air density and on the spacing and shape of the external terminals. In industrial use, these capacitors are unaffected by extreme variations of temperature, moisture and humidity, and can be made very robust mechanically with a consequent high order of capacitance stability. The power factor is low, the capacitors can carry heavy r.f. currents, and have a long life. The dielectric is self-healing, so that if the internal breakdown voltage is exceeded and flashover occurs, no permanent damage is caused, provided the arc is not maintained.

The limit of breakdown voltage across a perfect vacuum is determined by the material and shape of the electrodes. In theory, the voltage can be increased to the point where cold emission from the electrodes occurs, but this cannot be reached in practice because of the occluded gas given off by the metal used for the electrodes.

A typical construction developed by Messrs. Ferranti, Ltd., is shown in section in Fig. 9.4, and two typical capacitors are shown in Fig. 9.5.



Ferranti, Ltd.

FIG. 9.4. CONSTRUCTION OF VACUUM FIXED CAPACITOR

The main difficulty in construction is always experienced in the end seals; in early capacitors, tungsten–glass seals were used and outgassing arrangements were similar to those used in valve manufacture. Some recently developed vacuum capacitors use electrode cylinders made from high-quality nickel; another type uses copper. The capacitance between two cylindrical concentric electrodes is given by

$$C = Al_e/\log (r_2/r_1)$$

where C = capacitance, in pF,

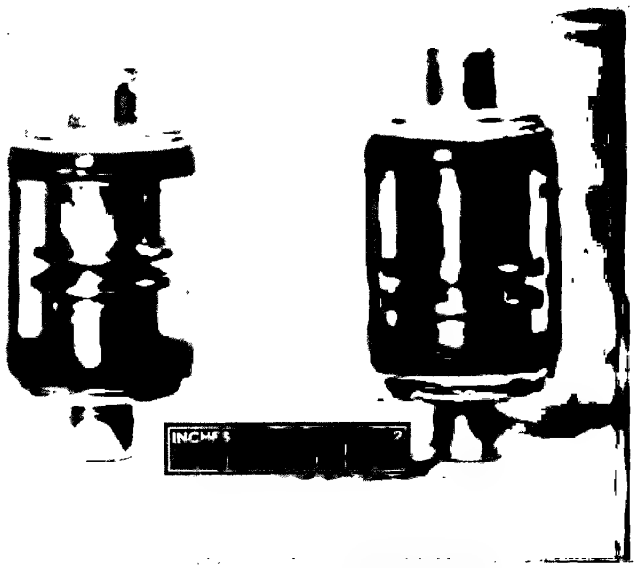
l_e = length of electrodes, in centimetres,

r_1 = radius of inner electrode, in centimetres,

r_2 = radius of outer electrode, in centimetres,

A = a constant.

In the type of construction using nickel electrodes, each set of electrodes is mounted on a mild-steel plate attached to a Kovar sealing ring which is fused into the glass envelope. The capacitor is assembled in a bell jar in an atmosphere of nitrogen, to avoid oxidation of the



Ferranti, Ltd.

FIG. 9.5. TYPICAL VACUUM CAPACITORS

nickel electrodes. R.F. heating is used to seal the Kovar rings to the glass.

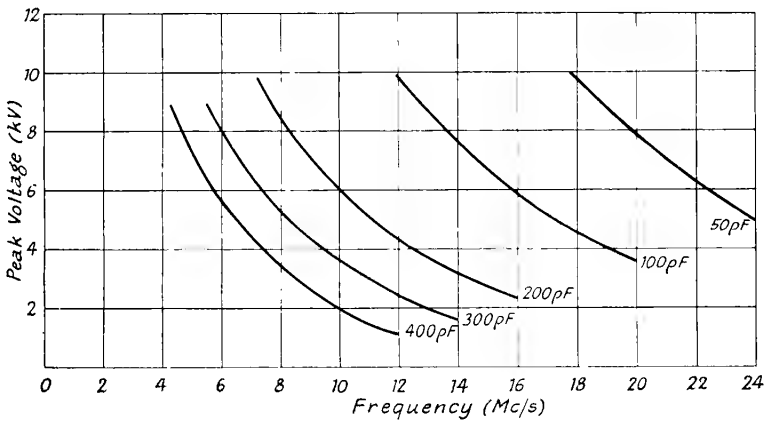
The capacitors are usually subjected to a temperature of approximately 400°C for several hours and then "spot knocked," a process which consists in charging up a relatively large capacitor and discharging it through the vacuum capacitor, which is in series with a suitable current-limiting resistor. The object of this process is to clean up minute projections on the electrode surfaces. This is repeated several times with the charging voltage raised progressively until a predetermined high value can be applied without further discharge. A barium getter is then fired by passing a current through it, and the capacitor is sealed by squeezing the piecing tube between rollers under high pressure, thus forming a cold weld. Contact caps of silver-plated brass are finally soft soldered to each end of the capacitor.

The characteristics of the vacuum capacitor are best suited for fairly low capacitance values up to the order of 500 pF. Above this

the capacitors become unduly large and are difficult to manufacture and the ceramic capacitor then becomes a serious competitor.

The characteristics of typical small vacuum capacitors manufactured by Messrs. Ferranti Ltd. are as follows—

Length	3·5 in.
Maximum diameter	1·75 in.
Capacitance	50 and 100 pF
Temperature coefficient	21 × 10^{-6} per deg C
External breakdown voltage (at 120 mm Hg pressure on capacitors with guard cylinders)	12 kV peak
(at 80 mm Hg pressure)	10 kV peak



G.E.C., Ltd.

FIG. 9.6. VARIATION OF VOLTAGE RATING WITH FREQUENCY FOR VACUUM CAPACITORS

The characteristics of larger vacuum capacitors, using copper electrodes, manufactured by the G.E.C. Ltd. are—

Length	6·5 in.
Maximum diameter	2·75 in.
Capacitance	50, 75, 100, 150, 200, 300, 400 and 500 pF (tolerance ± 2%)
Maximum peak working voltage	10 kV for sizes 75 to 300 pF 9 kV for sizes 400 and 500 pF

The variation of voltage with frequency for these capacitors is shown in Fig. 9.6.

GAS-FILLED TYPES

Gas-filled capacitors are used mainly as high-voltage components. The electrode structure is usually simple, consisting of an inner metal

tube suitably spaced inside an outer steel tube. Domed heads and stress distributors are used for voltages above 150 kV. The gas is usually compressed, and normal working gas pressures are around

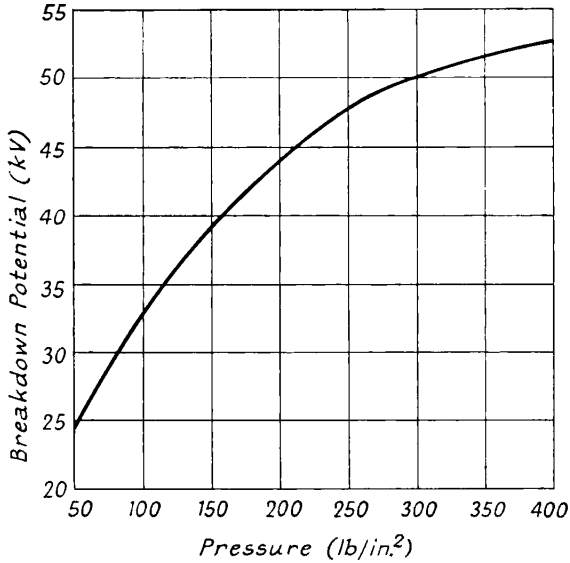


FIG. 9.7. INCREASE IN BREAKDOWN POTENTIAL OF NITROGEN WITH PRESSURE

150 lb/in². The gas may be air or nitrogen, and it must be clean and dry. A typical 250 kV capacitor of 50 pF would have a loss angle of less than 0·00001 rad. The temperature coefficient is higher than that of the vacuum types. The increase in breakdown voltage of nitrogen with pressure is shown in Fig. 9.7.

Chapter 10

SPECIAL AND EXPERIMENTAL TYPES OF FIXED CAPACITOR

Spun Thin-film Capacitors

A process which has been used experimentally for obtaining extremely thin, metallized dielectric films to form capacitors is as follows. A glass surface is silver mirrored (copper or aluminium may also be used) by one of the common metallizing processes, such as chemical reduction in aqueous solutions for silver, or thermal evaporation *in vacuo* for copper and aluminium. The dielectric is then applied to the metallized surface in the form of a solution by dipping, painting or spinning. Spinning is preferred, since more uniform layers may be obtained in this way. In spinning techniques the glass plate is revolved in a horizontal plane and a solution of the dielectric poured in the centre. Under the correct conditions the solution spreads itself in a uniform layer. The variables in the process are the strength of the solution, the viscosity, the temperature and the spinning speed. The speed most often used is about 500 rev/min. After spinning for a few minutes, during which the solvent evaporates, the layer is dried, by curing when necessary, and the composite layer of metal and dielectric is removed from the plate by floating it in a suitable liquid (usually water or alcohol) until the layer parts from the plate. After further drying the metallized foil is ready for cutting and assembly.

The advantages of the process are that thin uniform films of metallized dielectric can be obtained—for example, films of 0·0002 in. or less. In addition, if pinholes are present in the dielectric, the metallizing does not penetrate as it does when the metal film is applied to the dielectric. These techniques might be used in the development of sub-miniature capacitors for use with transistors.

Anodized-titanium Capacitors

Titanium metal readily forms a chemically inert oxide coating similar to that formed by aluminium, and it is possible that this film may possess similar insulating properties, modified by the extremely high permittivity of titanium dioxide. Experimental capacitors have been made at R.R.E. in the following way. Commercial high-purity titanium is anodized by direct current in various baths of concentrated solution of potassium dichromate, potassium phosphate, or common salt—the last is fully as effective in forming a dielectric layer and is

usually used. Oxidation is carried out by raising the voltage step by step from 1·5 to between 6 or 10 V, each step lasting until the current falls to a stationary value before the next increase is applied.

The capacitance of a circular disc electrode of diameter 1·4 cm and thickness 2 mm is 6 μF, the effective capacitance over both surfaces

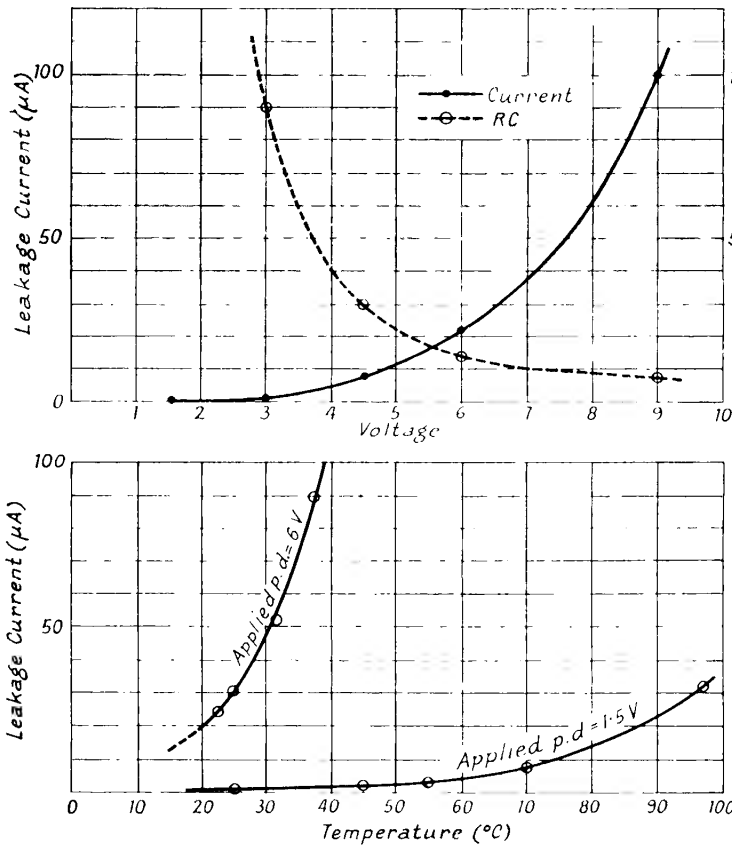


FIG. 10.1. LEAKAGE-CURRENT CHARACTERISTICS FOR EXPERIMENTAL ANODIZED TITANIUM CAPACITORS

therefore being 1·5 μF/cm.^{2} The working voltage is, however, only about 6 V. The leakage-current characteristics are given in Fig. 10.1.

The effect of d.c. bias on the capacitor is shown in Fig. 10.2, measured at 1·6 kc/s.

Since the measured capacitance is affected by a small d.c. bias the presence of charge should be detectable until it has leaked away completely, and in fact the "memory" may persist for a very long time.

Results obtained on a pair of titanium capacitors after initial charge are shown in Fig. 10.3.

"Dry" Aluminium-oxide Capacitors

Work has been carried out by the Electrical Research Association with the object of developing an experimental "dry"-type aluminium

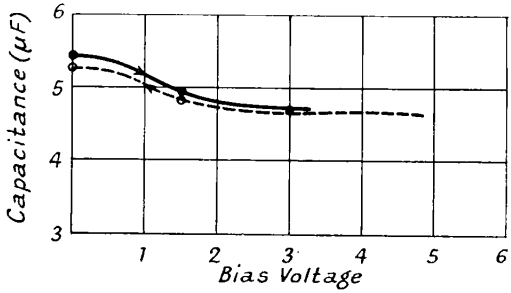


Fig. 10.2. Experimental Titanium Capacitor—Capacitance as a Function of Bias

electrolytic capacitor which would have a wide operating temperature range and an indefinitely long shelf life. It should also be able to operate on alternating current. Most of the faults occurring in normal

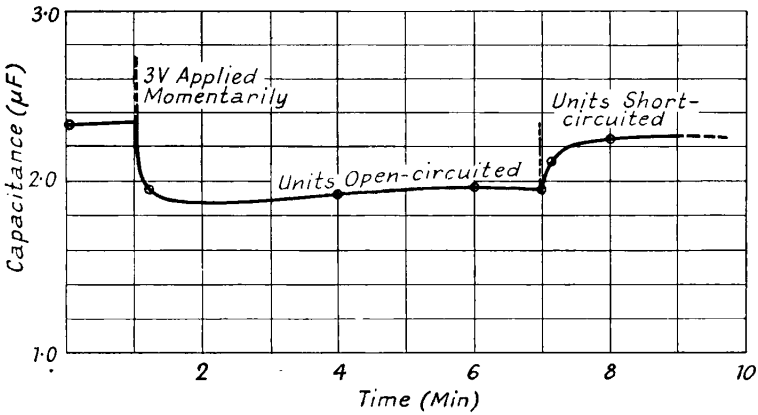


Fig. 10.3. Experimental Titanium Capacitor—Memory Effect

electrolytic capacitors are due to the electrolyte, and a study of the mechanism of operation of an aluminium electrolytic led to the development by the E.R.A. of an oxide dielectric which is metallized by evaporating aluminium on to the oxide.

High-purity aluminium foil is anodized first in an oxalic-acid and

then in a borate bath, as for a standard electrolytic capacitor. It is then dried out and a second electrode of aluminium is applied by evaporation. Contact sites are provided by an epoxy resin coating before the evaporation of the counter-electrode takes place.

The characteristics are comparable with those of a mica capacitor, especially for large capacitance values—

Capacitance (in case approximately 2 in. × $\frac{3}{4}$ in. dia.)	0·64 μF
Power factor (tan δ)	0·026 at 1,000 c/s.
Maximum working voltage	400 V d.c., or a.c. peak.
1-min. *RC* product at 200 V	10,000 Ω·F at 20°C.

A considerably higher capacitance (greater length of foil) can be wound into the same case.

Semiconductor *p-n* Junction Capacitors

The operation of a semiconductor capacitor is based on the fact that, when a *p-n* junction is reverse biased, the depletion layer acts as the dielectric of a capacitor whose "plates" are the undepleted portions of the *p*- and *n*-regions.

The *p-n* junction is formed either by alloying or diffusing an impurity of opposite type conductivity into *p*- or *n*-type semiconductor starting material (typically silicon or germanium with permittivities of 11·7 and 15·7 respectively.) Low-resistivity material gives the highest capacitance per unit area, due to a narrow depletion layer, but capacitors produced from such material have low breakdown voltages. A maximum capacitance of the order of 100,00 pF/cm^2 with a breakdown voltage of a few volts is possible for silicon junction capacitors.

The capacitance obtained in a given capacitor of this type is a function of the applied voltage, i.e.

$$C \propto \frac{1}{(V + V_0)^n}$$

where C = capacitance,
V = applied voltage,
V_0 "built-in" voltage, which for silicon at 25°C is about 0·8 V,
$n = \frac{1}{3} - 1$, depending on the carrier gradient at the junction.

With a forward bias of a fraction of a volt, the depletion layer vanishes, and the junction passes current in normal diode fashion. A simple *p-n* junction capacitor is therefore suitable for operation only where the applied voltage does not exceed about 0·5 V in the forward-biased condition.

A.C. Capacitors

In order to obtain a junction capacitor for use with alternating voltages greater than about 0·5 V, a *p-n-p* or an *n-p-n* structure can

be employed. In this configuration, one of the junctions is always reverse biased when voltage is applied. The capacitance per unit area is approximately half that of a single junction device of the same area and starting material, its exact value depending on the magnitude of the applied voltage.

Voltage-independent Capacitor

If a low-resistivity p-type layer is separated from a low-resistivity n-type layer by a thin layer of high-resistivity (intrinsic) material, a p^+-i-n^+ structure is produced, the capacitance of which when reversed biased will be that appropriate to the thickness of the high-resistivity layer and independent of the magnitude of the applied voltage.

Electrical Characteristics

The leakage current of silicon capacitors approximately doubles for every 11°C increase in temperature, and that of germanium capacitors, for every 8°C. This current, which is in the microampere range for silicon, gives rise to noise in the capacitor. A maximum temperature for the operation of silicon capacitors is usually fixed at 150°C.

The effect of temperature on capacitance depends on the impurity gradient at the junction; the capacitance variation of a silicon graded junction being a maximum of about 200 ppm/°C with several volts of reverse bias applied. An abrupt (alloyed) junction capacitor has a positive temperature coefficient of capacitance, typically 0·2 per cent/°C at $-0{\cdot}5$ V. This figure decreases with increasing reverse voltage bias and becomes 0·015 per cent at -6 V.

The maximum frequency of operation is closely related to the lifetime and thickness of the material used. Silicon p-n junction capacitors are available for use at frequencies up to several tens of gigacycles per second.

Availability and Application

Only p-n junction capacitors are commercially available as separate components, and these can be in either a glass bead or a metal can with a lead protruding from each end, or, for higher-frequency use, in a coaxial microwave fixture. Silicon capacitors with values up to several hundred picofarads at 0·1 V, and lower values with working voltages up to 130 V d.c. can be obtained.

Low-value capacitors have been specially designed for use in parametric amplifiers, while those of higher values are of use in voltage-tuned circuits. Another important application of junction capacitors is in solid circuits. Here any of the types mentioned can be fabricated integrally with the other circuit components.

Silicon Dioxide Capacitors

A miniature capacitor has been developed by Texas Instruments, U.S.A., which utilizes thermally grown silicon dioxide as the dielectric. Packaged in a flame-retardant resin encapsulant, 0·001 in. in diameter and 0·25 in. long, the device has capacitances ranging from 10 to 150 pF and is rated at 50 V operating over the temperature range

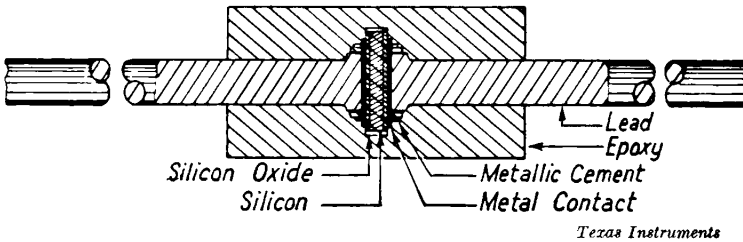


FIG. 10.4. CROSS-SECTION OF SILICON-DIOXIDE CAPACITOR (DISC CONFIGURATION)

from — 25° to 85°C. It has a low temperature coefficient of capacitance and high stability with life. Current tests indicate that a glass-to-metal sealed unit capable of operation at 175°C is possible.

Fig. 10.4 shows a cross-sectional view of the finished device. The dielectric is formed by thermally oxidizing low-resistivity single-crystal silicon (approximately 0·01 Ω-cm *n*-type) with steam at

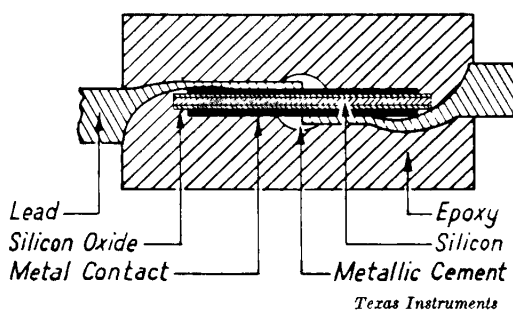
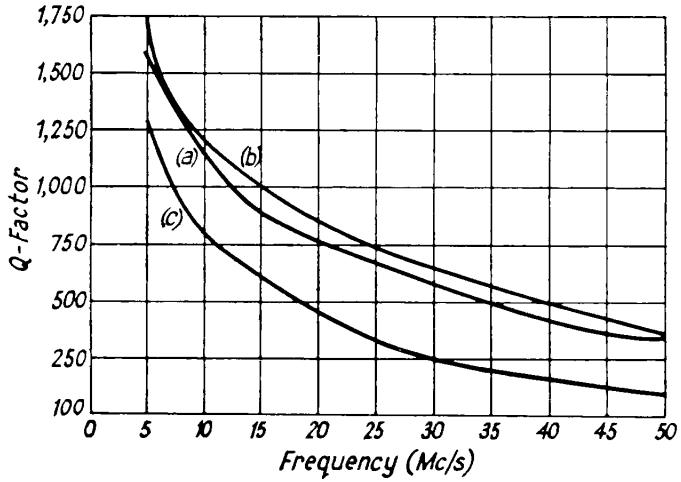


FIG. 10.5. CROSS-SECTION OF SILICON-DIOXIDE CAPACITOR (RECTANGULAR CONFIGURATION)

temperatures ranging from 1,000° to 1,200°C, giving film thicknesses from 5,000 to 25,000 Å. The forming time depends on the desired capacitance and the temperature of oxidation. Prior to oxidation, the silicon slices are thoroughly cleaned and the surface is prepared by a brief etch in a mixture of nitric, acetic and hydrofluoric acids. It has been demonstrated that the condition and nature of the silicon surface is of paramount importance in obtaining an impervious film. After

oxidation, a group of metallic contacts is sprayed on both sides of the oxidized silicon slice through a metal mask. These contacts are fired in, and individual 0·085 in. diameter discs are cavitroned from the large wafer using a precision cavitron assembly. Thus, each disc consists of two capacitors in series. Contacts to the metal-plate area are made by



Texas Instruments

FIG. 10.6. *Q*-FACTOR/FREQUENCY CHARACTERISTICS OF SILICON-DIOXIDE CAPACITORS

(*a*) 33 pF (*b*) 47 pF (*c*) 82 pF

means of a metal-filled thermosetting resin. The assembly is coated with a silicone varnish, and after the varnish has been cured, the capacitor is encapsulated in an epoxy resin.

In order to achieve the desired capacitance ratings, it was necessary to increase the plate area beyond that which could be obtained on the 0·085 in. diameter wafer. Fig. 10.5 shows a cross-sectional view of a rectangular configuration offering a threefold capacitance increase. The same results have been achieved by lapping one oxide layer off and increasing the plate area on the remaining dielectric layer, but the added handling was not economical. The variation of *Q*-factor with frequency is shown in Fig. 10.6.

CHAPTER 11

DIELECTRIC-FILM EVAPORATION AND DEPOSITION TECHNIQUES

RECENT work on microminiature techniques* has shown the necessity for thin dielectric films for use as capacitors. Films of resistive, magnetic and conductive materials have been developed, but films of dielectric materials have proved more difficult because of a number of fundamental and practical problems. A considerable study has now

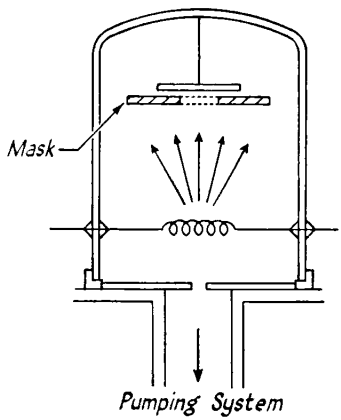


FIG. 11.1

been made of the physics of deposited dielectric films and some of the practical problems have been overcome. The use of very thin films enables a high capacitance to be obtained in a small space whilst also allowing rapid discharge to take place when required. Film thicknesses for these applications are usually measured in microns (1 mμ = 10^{-4} cm) or for very thin films in ångströms (1 Å = 10^{-8} cm).

The choice of substrate material is governed by a number of factors. Since the dielectric films are of the order of 1 μm in thickness, surface irregularities on the substrate must be considerably less than this. Unglazed ceramic substrates, however desirable from the point of view of their coefficient of expansion, are unlikely to have suitable surfaces, and ordinary microscope slides are often used because they are easy to

* DUMMER, G. W. A., and GRANVILLE, J. W. *Miniature and Microminiature Electronics*. Pitman (1961).

obtain and have an excellent surface. Substrates are normally degreased by conventional methods and are also given an ionic bombardment in the vacuum chamber before evaporation. The expansion of the substrate mainly controls the expansion of the much thinner layers, whilst the surface condition affects their adhesion.

Electrode materials must be easy to evaporate, good conductors and form stable adherent films on the substrate. Gold, copper, aluminium and

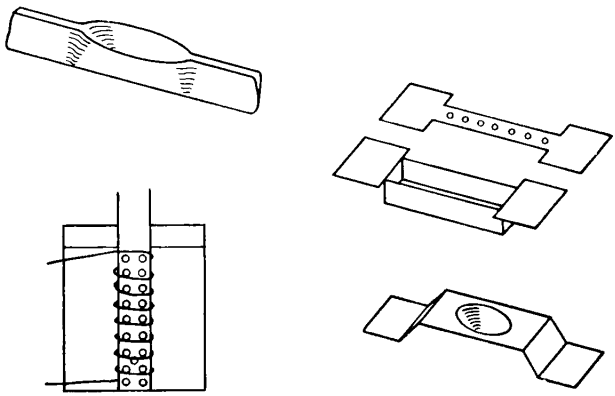


FIG. 11.2

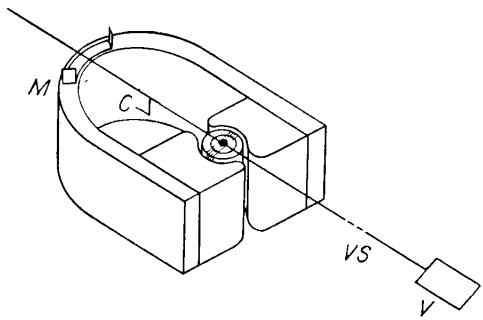
chromium have been used. Chromium will adhere very well to glass, and with a copper overlayer allows soldered joints to be made. It is unfortunate that its burn-out properties are worse than those of aluminium, owing to a much higher vaporization temperature. Aluminium electrodes give better electrical properties (i.e. higher-frequency operation) with the dielectrics investigated than do gold or copper.

A suitable dielectric must evaporate readily without either spitting or partial decomposition. It must adhere well to electrodes and substrate, be free from excessive internal stresses and resistant to atmospheric moisture. Both dielectric strength and permittivity should be high, coupled with low leakage. Small variation of these properties with increased temperature is desirable.

In vacuum deposition the material is heated in a high vacuum (10^{-5} mm Hg or better) to reach a temperature at which the particles are evaporated and, in the absence of gas molecules with which they would otherwise collide, travel in straight lines to condense on the surface to be coated (and elsewhere). This permits optical masking methods to be used. (*See* Fig. 11.1.) Dielectric materials in powder form are evaporated from boats, and some typical shapes are shown in Fig. 11.2. Deposition by sputtering, on the other hand, is carried out

at higher pressures (0·01–0·1 mm Hg), the material being released from the cathode by bombardment by gaseous ions. Maximum deposition rates are in general much less than those obtainable by evaporation, and distance between substrate and cathode is determined by the discharge conditions rather than by geometrical considerations.

Sputtering may be applied to some refractory metals having excessively high evaporation temperatures; and by sputtering in a



Plessey Co., Ltd.

FIG. 11.3. RATEMETER

M. Mirror scale
C. Counterbalance
VS Vane support (26 gauge aluminium wire)
V. Vane

reactive atmosphere, compounds (such as oxides) may be formed which would be decomposed during normal evaporation.

It has been necessary to develop a number of special methods to deal with the basic problems of control common to all evaporations—first to regulate the evaporation rate in order to control the thickness, stress properties, porosity and composition of evaporated films, as these are closely interrelated. This cannot be done, except very roughly, by measurement of the heating current or wattage, and while direct measurement of the source temperatures, coupled with a knowledge of the evaporating area, might prove adequate, the difficulties of such measurement are very great, not the least being the obscuring of the inspection windows by traces of evaporated material. One satisfactory method is the use of a continuous-reading ratemeter to measure the rate of flow of the vapour stream by the deflection of a light vane mounted on a galvanometer suspension, as shown in Fig. 11.3.

MEASUREMENT OF THICKNESS, STRESS, POROSITY, ETC.

The thickness of the deposited films may be measured directly by optical methods, but the accurate application of this method during deposition involves a knowledge of the optical constants of the film,

which may not be available. It might, however, be of great value in production processes dealing with known end-products.

For experimental purposes, it is more usual to examine the finished films. The thickness may then be determined by weighing, assuming a value for the specific gravity of the material. This assumption is occasionally wide of the mark and should therefore be made with due reservation. Direct optical measurement is possible using Tolansky fringes, but the method, while precise, is tedious and the results are difficult to interpret unless a smooth reference surface with a well-defined step is available.

In certain cases the thickness can be conveniently estimated from the

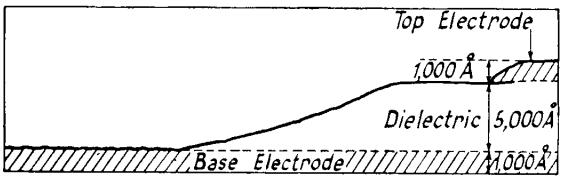


FIG. 11.4. SILICON-MONOXIDE CAPACITOR: TYPICAL PROFILE OBTAINED USING A TALYSURF MACHINE

Vertical magnification × 25,000
Horizontal magnification × 2,500

interference colour of the film, but this must be done with caution, as it requires a knowledge of the refractive index of the medium and also of the order of the interference band; again only average values will be given.

These limitations can be largely overcome by the use of high-resolution surface-measuring gear, of which the Talysurf is an example. This is as accurate as the fringe methods, is much quicker to apply and gives a detailed picture of the form of the surface in any required area. A typical measurement profile is shown in Fig. 11.4.

Deposited films are normally stressed either in compression or in tension. The amount of stress may be measured by the deflection of a flexible substrate such as a quartz fibre. The effects of stress are discussed later in more detail.

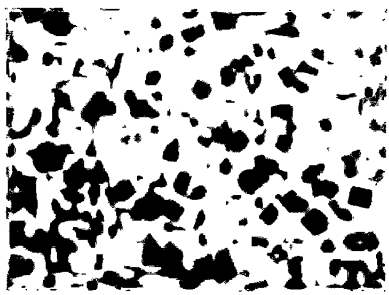
Film porosity can be studied optically by the refractive index method, or by weighing if the true thickness is known. Other methods such as rate of absorption of a vapour may be applicable to special films, but the interpretation of such experiments is difficult for films of the thicknesses considered.

A study of stresses in thin films has been made by Campbell,* and this has led to a study of accommodation coefficients and energy of adhesion to surfaces. For mixed deposit, the total deposition was found

* *See* Bibliography, p. 266, Blackburn and Campbell.

in some cases to differ from the sum of the separate constituents evaporated.

In an attempt to produce a stress-free film of mixed lithium fluoride and zinc sulphide, it was found that at least 30 per cent of the zinc sulphide was not in fact incorporated in the film, owing to scatter and non-adhesion effects. This work has been associated with electron microscopy for initial stages of deposition of dielectrics. This has shown that the nucleation mechanism for some dielectrics differs considerably from that of metals, in that the mobility of the nuclei is much lower and



Plessey Co., Ltd.

FIG. 11.5. LITHIUM FLUORIDE FILM DEPOSITED ON CARBON

growth is in plate-like form. It is possible for a dielectric film to acquire continuity at a much smaller thickness than is actually the case for a metal film. Fig. 11.5 shows a typical structure for a lithium-fluoride dielectric film.

CHEMICAL COMPOSITION OF DIELECTRIC FILMS

The problem of determining the chemical composition of a film has not yet been solved except in special cases. It cannot be deduced directly from the initial proportions of the materials evaporated.

The essential analytical problem is to determine the detailed composition of a small amount of evaporated material in the presence of a large mass of substrate, often having at least one constituent in common with the evaporated layer.

Micro-analysis of metallic films deposited on glass is relatively easy, but in oxide dielectric films small differences in oxygen content may greatly affect the electrical properties while being almost impossible to detect by chemical means. In certain cases spectrometric analysis at frequencies extending from ultra-violet to infra-red has been used with success, notably in the case of silicon monoxide and silicon dioxide mixtures, where the nature of the bonds present has been determined from the absorption bands observed. However, in most cases the structure is too complex to allow of easy interpretation.

The essential properties of a material for evaporation include low evaporation temperature, freedom from reduction during evaporation and ability to form a continuous film even at the required small thicknesses. Moreover, the films formed should be free from stresses so severe as to cause subsequent fracture. Table 11.1 shows the properties of some typical materials used.

Evaporation of Silicon Monoxide

This material is of somewhat indeterminate composition, often being regarded as an intimate mixture on a molecular scale of silicon and

Table 11.1

Material	Evaporation temperature at 10^{-2} mm Hg (deg C)	Permittivity	Capacitance of single plate 1 $cm^2 \times 1$ μm thick (pF)
Zinc sulphide (ZnS)	1,200	8	8,000
Silicon monoxide (SiO)	1,300	5	5,000
Silicon dioxide (SiO_2)	1,700	4	4,000
Magnesium fluoride (MgF_2)	1,400	5	5,000

silicon dioxide in nearly equal proportions. It appears, however, to have considerable stability as is shown by its widespread use in the optical industry as a lens coating material. This is a case in which oxygen deficiency has no great ill effect on the major electrical properties, although the special low-loss properties of pure quartz are not achieved.

It may be evaporated from a ground mixture of silicon and silicon dioxide or from resublimed silicon monoxide. A molybdenum boat, preferably with a perforated lid, is suitable; alternatively radiant heating from above with a tungsten spiral may be used. Rapid evaporation gives dense films, often yellowish in colour indicating some reduction. Slow evaporation (15 Å/sec or less) provides well-oxidized but perhaps less durable films.

Stresses in the deposited films are compressive, which reduces any tendency to craze as thickness increases. The presence of moisture and inadequate substrate preparation cause failure due to separation of the film from the substrate. A suitable cleaning technique for a glass substrate is to rub with neat Teepol, wash, dry, vapour degrease in isopropyl alcohol, and bombard ionically in the vacuum chamber at 250°C.

The films show a permittivity between 4·5 and 5·5 with a loss factor of 1–3 per cent at 1,500 c/s without appreciable variation up to 1 Mc/s.

The breakdown process is complex. At low voltages isolated sparks

occur. (It may be noted that a few pinholes are usually present in the dielectric before the application of external dielectric stress.) However, continuous breakdown does not become evident until at least 100 V have been applied to a 1 μm film. (This corresponds to a dielectric stress of 1 MV/cm at least.) Typical breakdown patterns for silicon monoxide are shown in Fig. 11.6. The highest breakdown voltages have

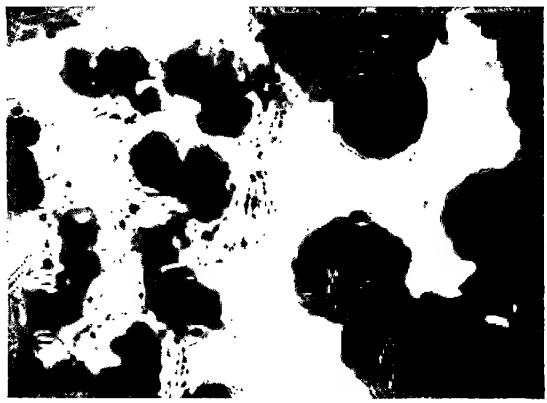


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FIG. 11.6. TYPICAL BREAKDOWN PATTERNS FOR SILICON MONOXIDE

been obtained using aluminium electrodes; this may be connected with the good burn-out properties of aluminium and its ease of oxidation in air. Similar results have been found for other dielectrics.

Leakage currents have been measured both in air and *in vacuo* (0·2–0·3 mm Hg), and it is found that the exponential dependence of current on applied voltage, characteristic of thin films measured in normal moist air, is replaced by an ohmic relation on evacuation, with great reduction in the leakage currents.

It has been found in the U.S.A. that a triple evaporation greatly diminishes the pinhole problem. The first layer of silicon monoxide develops pinholes which would propagate through the entire layer. However, if the process is stopped midway and a thin layer of silicon dioxide applied, the same pinholes do not continue through the second deposit. This complete evaporation sequence, including the production of electrodes, is performed without opening the vacuum chamber.

EVAPORATION OF OTHER MATERIALS

Silicon Dioxide

Numerous attempts to evaporate silicon dioxide have proved unsuccessful owing to the high temperature required and the tendency to reduction.

Silicon dioxide films with less than 0·5 per cent impurity (chiefly silicon monoxide) have been prepared by reactive sputtering in an oxidizing atmosphere. Slow deposition rates have prevented thicknesses above 0·2 μm from being formed. However, breakdown voltages up to 70 V have been observed.

Magnesium Fluoride

Magnesium fluoride is an example of an evaporable material of definite composition and crystalline form. Films are deposited in tensile stress, and for thicknesses much above 0·7 μm there is a severe tendency to craze. The permittivity is approximately 5. It has been used for capacitors in evaporated circuits, but it is doubtful whether it has any great advantage over silicon monoxide.

Zinc Sulphide

Whilst zinc sulphide is largely used in the optical industry for infra-red filters, it was originally supposed that its semiconducting properties would prevent its use as a dielectric. However, early experiments showed surprising promise, and later work under improved vacuum conditions established that zinc-sulphide capacitors could be stable on exposure to atmosphere.

Permittivities of 7·5–8·5 were obtained, the films being deposited in compressive stress, thus assisting the formation of thick layers with good mechanical properties.

Between aluminium electrodes leakage properties were excellent, but with copper and gold electrodes substantial currents were passed at low but not at high frequencies. The permittivity observed did not vary with electrode material, showing that in spite of leakage effects the main properties were those of a dielectric even at 1,500 c/s.

Breakdown stresses up to 150 V/μm (1.5 MV/cm) have been obtained for films prepared under carefully controlled conditions. It must be remembered that zinc sulphide is considerably less hard than silicon monoxide and is inherently more likely to react chemically with atmospheric moisture. It is also more likely to be affected by small quantities of conduction-generating impurities.

Cryolite

Cryolite (Na_3AlF_6) has been extensively studied because of the interest in the initiation of crazing and recrystallization processes in very thin films. It resembles magnesium fluoride in its properties, with a rather lower evaporation temperature. Continuous films have been prepared below 500 Å with breakdown strengths equivalent to 1 MV/cm and increasing at lower thicknesses. With electrodes other than aluminium these figures are slightly lower.

Glasses

Mixtures of silicon monoxide and other glass-forming oxides (those of barium, phoshorus, etc.) have been evaporated from separate boats to form glassy films by continuous deposition on aluminium foil. These films are flexible and give breakdown voltages up to 150 V/μm (600 V on a 4-μm film). Lead silicate glasses have permittivities up to 20.

HIGH-PERMITTIVITY MATERIALS

It has been shown that evaporated and heat-treated films of barium titanate ($BaTiO_3$) have ferro-electric properties, in particular a hysteresis loop characteristic of the bulk material but excited by only a few volts. Attempts to form such materials directly by evaporation of a preformed compound or from separate boats containing the constituents have not been successful. However, using reactive sputtering from a lead-titanium source it is possible to obtain permittivities up to 40 from a film nominally of lead titanate composition. This material has a breakdown strength of 0·6 MV/cm, which may be compared with the theoretical value for barium titanate of 0·75 MV/cm.

Titanium oxide (TiO_2)

Titania itself might seem a better material to use in view of its simple chemical composition and its widespread successful use as an optical film. However, it is exceptionally liable to reduction even in bulk, and so far all attempts to produce good electrical films have been unsuccessful.

Lanthanum Oxide

Work is being done in the U.S.A. on spontaneously oxidized lanthanum. In this process a thin layer of lanthanum is evaporated upon a conducting substrate. When exposed to oxygen, even at quite a low pressure, the lanthanum oxidizes immediately. Additional thickness is obtained by subsequent evaporations of lanthanum which can be monitored by conductivity while still in the vacuum system. After the requisite thickness of oxide is achieved, a suitable top electrode is applied. Properties are said to be similar to those obtained with silicon monoxide.

REACTIVE SPUTTERING OF TANTALUM OXIDE

A thin film of tantalum oxide is interposed between two aluminium-film electrodes, the whole structure being supported by a suitable substrate. The aluminium-film electrodes comprise the plates of the capacitor and the tantalum oxide is its dielectric.

The process is as follows. A fused-quartz microscope slide, size 25 × 76 × 1 mm, is prepared by washing in detergent, rinsing in

distilled water and then in isopropyl alcohol, and finally drying off by exposure to isopropyl alcohol vapour. This quartz substrate is then placed in a vacuum chamber, where it is further cleaned by ionic bombardment preparatory to its coating with six base electrodes (evaporated from 99·99 per cent pure aluminium), their thickness being approximately 2,000 Å.

The substrate now carrying the base electrodes is transferred to a sputtering chamber, where it is coated with tantalum oxide by the chemical or "reactive" sputtering process. In this process the oxide

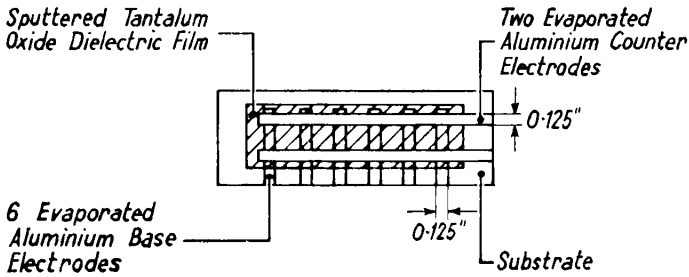

FIG. 11.7. CONSTRUCTION OF TWELVE TANTALUM-OXIDE CAPACITORS

is formed by sputtering from a tantalum cathode in an oxidizing atmosphere provided by leaking oxygen into the vacuum system through a needle valve. The cathode potential was 2,500 V and the cathode current density was maintained at 0·5 mA/cm², resulting in a sputtering pressure of 12 μm Hg. These conditions gave a deposition rate of 350 Å/hr, limited by the temperature rise of the substrate. The thickness of the dielectric films formed under these conditions ranged from 1,200 to 1,800 Å.

Finally the substrate is returned to the vacuum coating chamber, where two aluminium counter-electrodes are evaporated on to the surface of the tantalum-oxide film, so forming twelve capacitor elements.

A diagrammatic representation of a set of twelve capacitor elements made as described above is shown in Fig. 11.7.

Capacitors formed in this way, for test purposes, have capacitances of 0·1 μF/cm² and tan δ values of less than 0·01 up to 30,000 c/s. Unprotected films have withstood d.c. breakdown voltages up to 14 V for an 1800 Å film; frequency characteristics are shown in Fig. 11.8.

REACTIVELY-DEPOSITED SILICON NITRIDE

Silicon-nitride capacitors produced by pyrolytic deposition show acceptable properties up to 600°C and may fill a need for a

high-temperature capacitor. A mixture of silicon bromide vapour with deoxidized hydrogen and nitrogen is brought into contact with a 5-mil molybdenum substrate held at 960°C. The rate of build-up of silicon nitride (Si_3N_4) is controlled by the flow rate of the silicon bromide.

A rate of formation of 0·5 mil/hr is recommended for best results, and most films studied have been of the order of 0·5 mil thick. The molybdenum substrate serves as one electrode; for the other, molybdenum is deposited from molybdenum pentachloride in a hydrogen stream with the silicon nitride surface at 800° C. In 5 min,

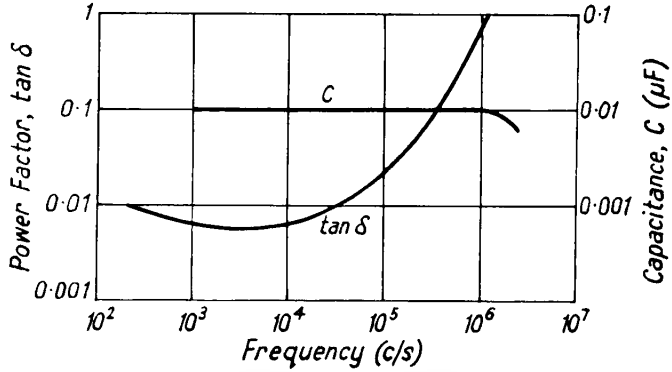

FIG. 11.8. POWER-FACTOR/ AND CAPACITANCE/FREQUENCY CHARACTERISTICS OF TANTALUM-OXIDE CAPACITORS

0·5 mil of molybdenum can be produced. Experimental capacitors have shown power factors at 1 kc/s of 0·0001 up to 300° C.

THIN FILM DEPOSITION BY GLOW DISCHARGE

An electric current can pass through a rarefied gaseous atmosphere if there is a strong enough electric field. When the gas is at a pressure of about 5 mm Hg, the current will cause the gas to glow. The current is carried by a plasma consisting of electrons and positive ions produced by the electric field. Such glow discharges are used frequently as light sources, the filling being an inert gas or mercury vapour.

A new process* uses the vapour of an organic material. Under the influence of the discharge, molecules of the vapour become ionized and a deposit is formed on the surface of a current-carrying electrode. Thin films may be formed also on non-conductive surfaces interposed in such an electric field.

Previous investigators noted the formation of polymers upon

* Radiation Research Corporation, U.S.A.

treatment of organic monomers in gas discharges. Others studied the effects of ionizing radiation on polymerization reactions, but little attention was paid to the electrical properties of films formed under these high-energy conditions. Jerome Goodman, inventor of the glow-discharge deposit process, directed special attention to the

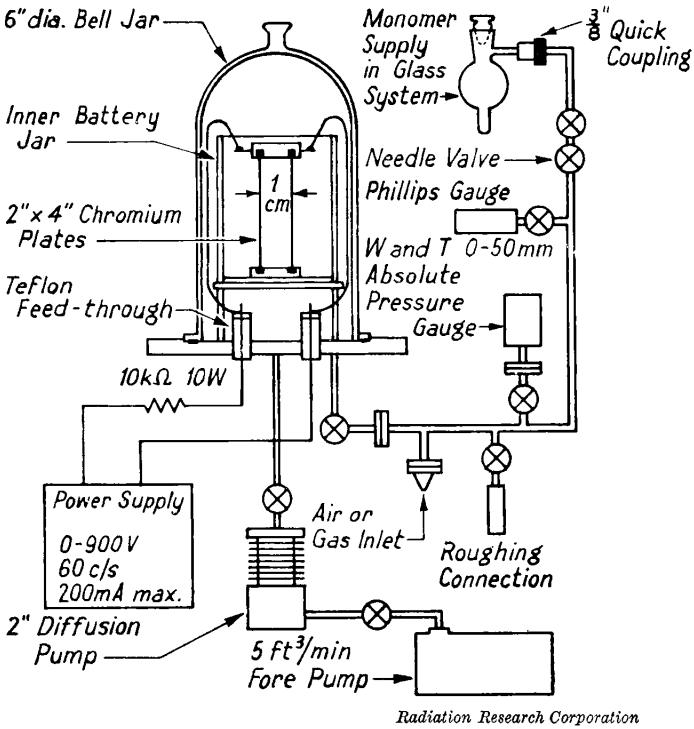

FIG. 11.9. THIN-FILM PRODUCTION

electrical properties. It is claimed that the process creates a pinhole-free surface even when only 0·02 mil thick. The films have excellent chemical, physical and electrical characteristics, since the polymerization is finely controlled in a virtually uncontaminated atmosphere.

Fig. 11.9 illustrates experimental organic thin-film production. The bell jar is evacuated, and a voltage of 450 V is applied to chromium-plated electrodes. A valve is then opened, permitting monomer vapour to flow from supply to bell jar. The vapour pressure is allowed to rise (to about 5 mm Hg) until vapour ionization is evidenced by the

emission of visible light from the plasma. The flow of vapour is controlled until the monomer supply is used up. The process is continued until a film of the desired thickness is produced.

General

It is necessary to remember that the limiting frequency response of a thin-film capacitor is determined at least as much by the resistance of the leads and plates as by the property of the dielectric itself.

It is becoming more and more obvious that ultra-high vacuum techniques are required to improve the properties of deposited films. It is only recently that suitable equipment has become available, other than on a very small scale, but it has already been shown that the properties of magnetic, resistive and superconducting thin films vary greatly with the degree of vacuum during deposition.

Chapter 12

FAULTS WHICH MAY OCCUR IN FIXED CAPACITORS

One of the most common faults in fixed capacitors is the deterioration of the insulation resistance caused by the penetration of moisture through incomplete sealing. Although many types are now well sealed, it is a difficult problem to seal a capacitor completely and thoroughly at low cost, and without creating production difficulties. The deterioration occurs mainly under arduous service conditions, but can occur under normal conditions in such places as India. In ordinary domestic radio, room and valve heat reduce the effect. Varying humidity and temperature cause moisture vapour to be sucked in, either because of molecular penetration of the materials used or along the connecting leads to the electrodes. This vapour is trapped, remains as moisture and, in turn, lowers the insulation resistance, causes loss, and in some cases, breakdown of the component.

In low-voltage impregnated-paper capacitors the main faults which have occurred have been due to high leakage currents and short circuits. Of several probable causes of high leakage currents in this class of capacitor the commonest is deterioration of the impregnant. The use of impure impregnants gives rise to many failures, one cause of deterioration of the impregnant being that rosin leaks in during soldering, in the course of manufacture. In some equipments ambient temperatures higher than normal have been used, and with a paper dielectric, deterioration of the paper itself, caused by dehydration, becomes rapid above 70°C. Short circuits and burn-outs have probably been due to excessive voltage surges, in which the dielectric breaks down at its weakest spot. The progressive deterioration of the impregnant would be a contributory cause. The date of manufacture of this type of capacitor is important, as old capacitors may suffer from ageing effects during storage.

Pitts* has given three main causes of failure of fully sealed paper-dielectric capacitors—

(*a*) Conducting particles in the tissue.

(*b*) Substances which can dissociate and cause electrochemical deterioration.

(*c*) Voids.

* "The reliability and life of impregnated-paper capacitors." *Proc. Instn. Elect. Engrs.* **106A** (1959), 397.

Voids can be avoided with fluid impregnants, but the extent to which (*a*) and (*b*) affect the mechanism of failure depends on many factors, for example d.c. or a.c. operation, voltage stress, number of papers, temperature, etc.

With all tubular capacitors the effect of severe vibration such as that

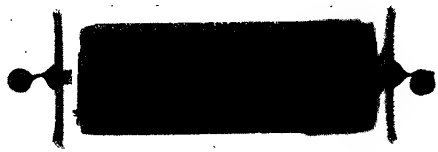

FIG. 12.1

encountered in aircraft or guided missiles may be to break the internal connections between the foil and the outer contact. An example is shown in the X-ray photograph of Fig. 12.1.

Metallized-paper capacitors, although normally self-healing, sometimes become faulty when used in series with a high resistance.

TABLE 12.1. MAXIMUM PERMISSIBLE SERIES RESISTANCES

Source Voltage	Capacitance (μF)					
	0·1	0·2	0·5	1	2	5 or more
V	MΩ	MΩ	MΩ	MΩ	MΩ	MΩ
150	(*c*) 0·6	(*c*) 2·5	(*d*) 3	(*d*) 3	(*d*) 3	(*d*) 3
125	(*a*) 0·001 2	(*c*) 1·3	(*d*) 2	(*d*) 2	(*d*) 2	(*d*) 2
100	(*a*) 0·001	(*b*) 0·2	(*c*) 1·2	(*d*) 1·2	(*d*) 1·2	(*d*) 1.2
75	(*a*) 0·000 8	(*a*) 0·000 8	(*c*) 0·4	(*c*) 0·7	(*d*) 0·7	(*d*) 0·7
50	(*a*) 0·000 5	(*a*) 0·000 5	(*a*) 0·000 5	(*c*) 0·13	(*c*) 0·3	(*d*) 0·3

Accelerated life tests by the Post Office Research Laboratories have shown that faults may occur when 0·5-μF capacitors are connected to an 80-V supply through a resistance of 13 MΩ or more.

Maximum permissible series resistances for reasonably safe operation are given in Table 12.1.*

Several different cases arise, according to the relative values of the supply voltage, V, and the minimum self-healing voltage, V_h.

* NEW, A. A., and LYNCH, A. C. "The failure of metallized-paper capacitors used with large series resistances." *Proc. Instn. Elect. Engrs.* **109**B, Suppls. 21–22 (1962), 496.

(*a*) If $V < V_h$, the energy for self-healing must come from the external circuit, and experiment shows that a current of 100 mA is needed. This condition occurs for the entries marked (*a*) in the table.

(*b*) If $V \simeq V_h$, a strict calculation forbids any useful value of external resistance. But the calculations are based on rough estimates, and surprisingly large external resistances can be allowed without more than 10 per cent reduction in the stored energy. This leads to the entry (*b*), derived from the formula used for case (*c*), but assuming V_h to be 5 per cent less than that calculated above.

(*c*) If $V_h < V < 2V_h$, the limiting condition occurs when the power dissipated within the capacitor at voltage V_h is equal to that

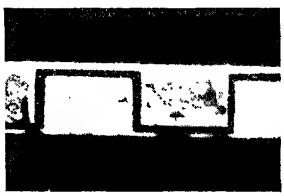

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FIG. 12.2

needed for triggering. Then $V_h^2/R_c = P_0$; and $V_h/V = R/(R + R_c)$, from which $R = V_h(V - V_h)/P_0$, and this expression leads to the entries marked (*c*).

(*d*) If $V > 2V_h$, the maximum permissible external resistance is such that the triggering process occurs at half the supply voltage, because this is the condition giving the maximum power dissipation within the capacitor for a given supply voltage.

Then $P_0 = V/4R$, so that $R = V^2/4P_0$, and the stored energy exceeds the minimum for self-healing. This expression gives the values marked (*d*).

When metallized-paper capacitors are overloaded by excessive temperature, the cause of failure will be a gradual removal of metal from one of the electrodes by electrochemical action as shown in Fig. 12.2. The clear metal strip at the top of the photograph is beyond the overlap of the electrodes when the foil is wound. The dark areas showing the removal of metal when the foil is wound can be clearly seen.

In moulded silvered-mica capacitors failures have occurred due to the slow building-up of conducting material with time across the dielectric, and cases have occurred where the silver has migrated over the surface of the mica, causing low insulation resistance followed by voltage breakdown. This may be caused by corona effects from

excessive alternating voltage, or it may be due to the presence of electrolytic impurities in combination with moisture inside the moulded case.

There are sometimes intrinsic faults in the mica itself, in spite of the rigid inspection and testing to which the mica sheets are subjected. When failure is due to a defect in the mica (e.g. black spot) it often takes place at a low voltage. During the manufacturing process, the mica plates may be damaged, an electrode may be loose, giving a high value of tan δ, or the thermal contraction of the soldered connection to the silver electrode may cause it to tear away on cooling. Short circuits may occur if grit or dust particles are enclosed before

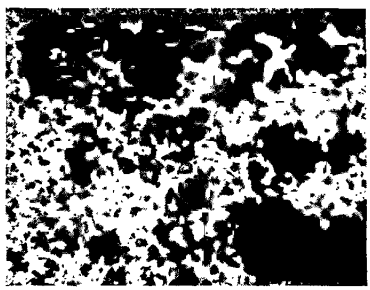

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FIG. 12.3. OPTICAL MICROGRAPH OF ANODIZED TANTALUM SHOWING CRACKS IN THE OXIDE

× 100

the plates are pressed together. These faults, however, are extremely rare in modern capacitors.

In the course of time, silvered-ceramic capacitors may suffer from migration of silver away from the silvered electrode areas, and in some cases actual breakdown has followed the path of one of these growths through a flaw in the ceramic.

In electrolytic capacitors, difficulties due to corrosion caused by leakage of electrolyte through the case are now rare; they were due mainly to faulty assembly, and this problem has been overcome. High leakage currents are often caused by depolarization during storage, and old capacitors of this type should be re-formed before use.

The electrolyte is usually the main cause of failure in aluminium-oxide electrolytic capacitors. At high temperatures drying out of the electrolyte eventually produces a high power factor and loss of capacitance. At low temperatures the electrolyte freezes and causes a high power factor and low capacitance. Any corrosion effects are generally attributable to the electrolyte. Surges over the working voltage in this type of capacitor should be avoided in the design of equipment, by using, where necessary, indirectly heated rectifier valves, delay switches,

etc.; otherwise "scintillation" will occur with consequent breakdown of the capacitor.

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FIG. 12.4. ELECTRON MICROGRAPH OF ANODIZED TANTALUM SHOWING EFFECT OF SCINTILLATION
× 7,500

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FIG. 12.5. ELECTRON MICROGRAPH OF ANODIZED TANTALUM SHOWING TWO FIELD-CRYSTALLIZED AREAS
1,500

The onset of breakdown in tantalum electrolytic capacitors depends on the particular oxide electrolyte system and on the voltage, temperature and pressure. All the types of breakdown are accompanied

by luminous phenomena. For instance, with certain kinds of electrolyte, patches of non-uniform glow spread rapidly across the oxidized anode and the oxide dielectric layer cracks as in Fig. 12.3 (p. 212).

Scintillation can occur with most types of oxide–electrolyte system. Fig. 12.4 shows the effect of one such spark on the tantalum oxide film.

A form of breakdown which limits the use of tantalum anodes at high voltages and high temperatures is field crystallization. In this the original amorphous oxide is displaced by a crystalline oxide which spreads across the surface of the anode (Fig. 12.5).

Leaks and the unwanted production of pulses have caused difficulties with high-voltage capacitors. Mechanical leaks can be avoided by proper sealing of the can, but the spontaneous pulsing and noise generation by capacitors is a fundamental problem and is discussed below.

RANDOM PULSE AND NOISE GENERATION IN CAPACITORS

"Pulsing" and random noise generated in capacitor units may have very varied origins, and only a little is known about these, especially infrequent noise pulses which would not be noticed in the ordinary tests which capacitors have been subjected to in the past. Certain sources of noise have been well established during such tests, and it is possible that they may persist under other conditions in causing random pulses, and thus be important sources of error in counting circuits, although for normal purposes the component is completely satisfactory.

Five possible sources of noise or random pulses are considered here.

(1) *Internal Discharge.* The best known of these normal sources is the incipient internal discharge which precedes normal breakdown. This phenomenon is due to local ionization under high stress when there are any air occlusions or voids. Under a.c. excitation, this leads to a new discharge twice per voltage cycle: its onset is an indication that the component has been stressed beyond the safety limit, and the detection of this noise forms the basis of the E.R.A. non-destructive test. Under d.c., a pulse of current may be followed by a quiescent period during which stress is built up again by leakage or by general relaxation of the dielectric until there is another flash.

It is quite feasible that such local pulses might be built up under d.c. stresses considerably lower than those at which the noise becomes appreciable in normal tests, owing to the indefinite time available for such stresses to accumulate. Noise caused in this way, however, may be expected to fall off if the stress is reduced by connecting elements in series for a given voltage.

In badly designed or faultily assembled components, the existence of incomplete leakage paths, or of exposed points and edges at which corona and sparking can form, will obviously be bad sources of noise;

these can be regarded as extreme, and removable, causes of incipient noise.

(2) *Scintillation, or Flutter.* This is a possible source of random noise in radio-frequency components of silvered-mica or silvered-ceramic type. It consists of random jumps in capacitance, and therefore of charge stored. It is attributed to incomplete adhesion of the silver to the material of the dielectric so that, when there is thermal expansion or mechanical shock, complete areas are jolted in or out of circuit. This source of noise is not to be expected in large paper-dielectric capacitors, where foil electrodes are usual, except in capacitors having inserted tab contacts. These often make poor contact when carrying small currents, and should not be used if freedom from noise is important. It can, however, occur in mica and ceramic elements, although rarely in modern types. Correct metallizing, and in some cases electroplating, overcomes the fault. From its nature, however, it cannot be assumed that a component will not become liable to the fault as a result of rough usage—probably any such tendency would be brought out by subjecting a sufficient number of specimens to stringent high- and low-temperature cycling.

(3) *Dielectric After-working.* At very low rates of occurrence, it is possible that the effects of dielectric after-working may produce noise-pulses, and unfortunately this is most marked with the good dielectrics such as polystyrene and quartz. The stressing of the whole material is not released at once, but regions are left in a stressed condition, which is relaxed by processes of a viscous nature but is taken up in the structure, thus restoring some of the original polarization. A similar process may be expected to occur during charging, and the temporary release of such stresses may be represented by impulses of voltage. Liquid dielectrics might be used to reduce this effect.

(4) *Polymerization.* It is known that in plastic materials such as Polythene, polymerization is incomplete and will continue with time, so that eventually stresses may be built up which may possibly be released either as a slow variation, or as an incipient pulse.

(5) *Radiation.* The action of light, or of radioactive particles and X-rays, on all the "good" dielectrics—Polythene, quartz, mica—produces ionization, and is therefore a potential source of noise, especially in components of small capacitance. It is of interest that a single crystal of anthracene, a pure hydrocarbon, is a standard form of β-ray counter—the scintillations being photo-electrically magnified. Hence, if components of these materials are exposed to radiations, some noise may be expected as a result, and there can be no protection from such noise except by adequate shielding and disposition of the apparatus.

In ferro-electrics there is the analogue of the Barkhausen effect. This is well established and produces large voltage pulses.

The above list of sources of noise may not be exhaustive, and mechanical movements of electrodes, etc., due to thermal expansion overcoming friction, may cause pulses to be generated, either by change of capacitance or contact resistance or by tribo-electric effects, but it is a summary of the principal causes of trouble which, from present limited knowledge, may be expected to cause noise. The summary shows especially the causes of noise at low frequencies which would not be detected on ordinary capacitor tests.

CHAPTER 13

FUTURE DEVELOPMENTS IN FIXED-CAPACITOR DESIGN

THE three main aims of future developments will be –

1. An improvement in reliability of existing types, particularly miniature and electrolytic capacitors.
2. The development of evaporation and sputtering techniques for microminiature assemblies.
3. The development of semiconductor types of capacitor.

Other possible future capacitor developments are discussed under the headings of the various dielectrics in the same order as the previous chapters.

PAPER DIELECTRICS

Future developments will probably be concerned with the improvement of reliability together with small size. Reduction of size may be achieved either by reducing the thickness of the tissue still further, or more likely by increasing the permittivity of the impregnant used. There will be a continuing requirement for a low-cost component for use in transistor circuits. New high-permittivity materials for impregnation may be developed, and more work may be done on mixed dielectrics (paper plus plastics) for special applications. Studies of the reliability of miniature capacitors will increase, and the causes of failure will be remedied, giving longer lives. For large capacitors used in modulators, etc., more rapid discharges will probably be obtained by the use of matching sections.

METALLIZED-PAPER DIELECTRICS

Metallized-paper dielectrics will continue to be used and may supplant foil types for many purposes in transistor circuits.

MICA DIELECTRICS

There are few new developments to be expected from natural mica, but the use of synthetic mica may increase if the cost can be reduced. Some new synthetic micas with higher permittivities may be developed. Mica capacitors will probably continue to be used for specific applications, particularly high power and where high stability and close tolerances are required.

Ceramic Dielectrics

Low-voltage ceramic capacitors for use in transistor circuits will probably be further developed, and their reliability improved by a detailed study of failure mechanisms. Capacitors capable of rapid discharge will be developed mainly for use in computer circuits. Barrier-layer types may have some uses as very-low-voltage capacitors, but difficulties in their manufacture must be overcome. Special types may be made for high-power high-voltage work to replace some paper capacitors in modulators where large capacitances and voltages of 10,000 V or more may be required. For the future, work will be done on sputtered and evaporated capacitors from multiple sources to provide medium to high permittivity. Although this is theoretically possible, considerable effort will have to be put into these techniques before even experimental capacitors become available.

Glass and Glaze Dielectrics

No new developments are envisaged in the future apart from improvements in production techniques and consequent improvement in reliability. The stability of glass capacitors is good, but for use in filters, where high stability has great value, large numbers of individually different predetermined capacitance values are required. This suggests the development of a means of adjustment of such capacitors. There is the possibility of improved glass as a material with higher permittivity, and also some work is being done on evaporation techniques using glass-like materials.

Plastic Dielectrics

It may be possible to improve the voltage ratings of polystyrene capacitors by impregnation techniques; this would be valuable as these capacitors can be considered frequency independent. Polycarbonates and polypropylene are being used for higher-temperature operation, and no doubt many other plastics will be experimentally developed, although deterioration by the catalylic action of copper at high temperatures must be guarded against. The formation of thin polymer films on metal substrates under the influence of discharge in monomer vapour may result in new plastic-dielectric capacitors.

Electrolytic Capacitors

A development which is likely to have interesting results is the dry-type tantalum electrolytic capacitor, in either the pellet or foil form. This should result in very low leakage, better frequency response and higher storage capacity. Higher-purity tantalum is expected to provide a more reliable capacitor, although high reliability is already being achieved in both types. Long-term studies of the mechanism of

breakdown will result in still further improvement in reliability. Flat tantalum capacitors produced by oxidizing techniques have been developed and may have a use in microminiature assemblies. The reactive sputtering of tantalum is also promising and will provide flat-type capacitors with permittivities of 22.

Evaporated and Deposited Dielectrics

With the advent of microminiature techniques, evaporation, sputtering and other methods of producing dielectrics are likely to be still further expanded on the lines described in Chapter 11.

Semiconductor Capacitors

In addition, semiconductor solid-circuit capacitors will be the subject of intensive study and new developments are likely. The use of variable capacitor elements in devices such as varactors, etc., will also continue. Possibilities in solid-state "capacitive effects" will undoubtedly be studied intensively.

General

Capacitors capable of very rapid discharges may also be required for many applications such as explosive forming of metals, and no doubt special capacitors will be needed for some of the new applications resulting from present studies of fundamental physics.

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Some general reviews are included, and a number of patent references, together with brief précis of the patents. The bibliography has been arranged in approximate date order and subject sequence.

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